A Method for Testing the Amount of Deformation and Level of Force Required to Produce Permanent Injury to the Dentition

The thesis is submitted in fulfilment of the requirement for the degree of

Masters in Engineering

By

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2016

Statement of Original Authorship

The work contained in this thesis has not been previously submitted to meet requirements for an award at this or any other higher educational institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

QUT Verified Signature
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26 July 2016

Acknowledgements

The completion of this thesis would not have been possible without the constant support and encouragement of my Supervisor Professor Mark Pearcy. Thank you for being so understanding and patient with me, but mostly thank you for believing in my potential and providing the drive I needed to complete this milestone. Your guidance, commitment and knowledge inspired me every step of the way, and will continue to throughout my researching career. My warmest thanks also extend to my assistant supervisor, turned Supervisor, Associate Professor Clayton Adam for his guidance, support and advice throughout my learnings.

I would also like to thank Dr Thomas Gibson and Dr Chris Farrell who imparted great knowledge, support and wisdom to me throughout the project. Furthermore, I would like to thank Ian Mellor, Jim Walsh, Roland Steck, Caroline Grant and Lance Wilson for their help and support at the most random of times, with the most random of tasks. Without them a lot of the testing performed and analysis undertaken in this project would not have been possible, particularly Caroline for all her assistance with the data analysis guidance.

Lastly, but certainly not least I wish to thank my husband Adam, and my family, for believing in me, for giving me the time and space to work on this project, and for the unfaltering support in my abilities to complete such a project, through the tears, stress and breakdowns. This is as much an accomplishment for you as it is for me.

Abstract

Sporting injuries are the cause of between 3% and nearly one third of dental injuries occurring each year. Astoundingly, there is a 95% chance of permanent disfigurement to the most visible upper front teeth due to an impact to the mouth. Although sporting activities which utilise mouthguards have a reduced occurrence of tooth injury compared with those which don't, the single Australian standard which exists for mouthguard testing is a handbook of guidelines based on testing of the unformed mouthguard material only. Although the rate of incidence of dental injury is mentioned in the literature, the focus of mouthguard protection currently lies in the protection offered to the jaw and tempero-mandibular joint (TMJ) and the brain due to the more serious nature and long term detrimental effects of mild traumatic brain injuries (MTBI), and skims over the protection offered to the dentition. The effectiveness of mouthguards in preventing dental injuries also appears to be poorly understood because the biomechanical characteristics of the dentition and their responses to impacts and associated injury tolerance levels have not yet been defined. Detailed understanding of this information would allow for the major influencing factors on the extent of damage sustained by the dentition to be defined and subsequently factored into the design of a mouthguard to enable protection against such damaging factors. This study aimed to explore the possible methods of investigating tooth injury biomechanics, and develop a method for testing the amount of deformation and level of force required to produce permanent injury to the dentition. An apparatus was designed and manufactured to house an intact tooth and maxilla post-mortem human subject (PMHS) specimen and a test method proposed utilising an Instron machine to deliver quasi-static loads to the teeth and an Optotrak Marker system to record motion during the loading. In a series of pilot studies using rapid prototyped (RP) specimens and then finally PMHS specimens, the capabilities of the test apparatus and specimen housing to withstand the desired loading were shown, and the ability of the Optotrak Marker system to successfully trace motion on the scale required was demonstrated. No visual tooth injury was produced during testing. The testing did, however, define some mechanical characteristics of the teeth tested. The findings of this work point the way toward future refinements necessary to develop a robust and repeatable method capable of measuring dentition biomechanics and injury thresholds.

Key Words

Dentition, Teeth, Mouthguard, Biomechanical response of teeth, Biomechanical properties of teeth, Tooth injury biomechanics, Mouthguard effectiveness, Mouthguard protection

Definitions

Dentition – The teeth and their supporting structures
Supporting Structures – The periodontal ligament, the root, the gums and the maxilla alveolar bone
Biomechanical Response – The shape of the load deformation curves generated by the dentition under a predefined load
Tooth Compliance – The inverse of tooth stiffness, or, the amount of movement of the dentition under a defined load relative to the maxilla (mm/N)
Tooth strength – The amount of load (N) a tooth can withstand before injury occurs
Injury Tolerance – The load and or deflection at which injury to the dentition occurs

Abbreviations

ADA – American Dental Association
FDI – International Dental Federation
HIE – Human Impact Engineering
MERF – Medical Engineering Research Facility at QUT
MG – Mouthguard
MRC – Myofunctional Research Company
MTBI – Mild Traumatic Brain Injury
PDL – Periodontal Ligament
PMHS – Post Mortem Human Subject
QUT – Queensland University of Technology
TMJ – Temperomandibular Joint

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1. Introduction

The Australian Dental Association (ADA) and many published authors have identified sporting activities as one of the principal causes of cranio-maxillofacial injuries, with approximately 20% of sports related hospitalisations each year involving injuries to the head region [1-5]. In particular, sporting injuries are the cause of between 3% and nearly one third of dental injuries occurring each year [3, 6, 7]. Astoundingly, there is a 95% chance of permanent disfigurement to the most visible upper front teeth due to an impact to the mouth [7]. Although sporting activities which utilise mouthguards have a reduced occurrence of tooth injury compared to those which don’t [7], the single Australian standard which exists for mouthguard testing is a handbook of guidelines based on testing of the unformed mouthguard material only [8]. Additionally, there is no surrogate test head-form with biofidelic jaw and teeth available that allows impact injury to the teeth to be investigated.

Currently, extensive research work is being carried out around the world to define the effects of mouthguards on Mild Traumatic Brain Injury (MTBI), or concussion, due to the protection offered to the jaw, tempero-mandibular joint (TMJ) and brain from impacts to the head [3, 5, 6, 9-28]. None of these studies consider the effects of mouthguards on the teeth and their supporting structures (i.e. periodontal ligaments), or assess the effectiveness of mouthguards in mitigating injury to the teeth and supporting structures.

This study characterises the human dentition in a biomechanical sense; investigates and defines sporting impacts to the teeth; and characterises the types of injuries seen as a result of those sporting impacts. This study also explores the possible methods of investigating tooth injury biomechanics, and combining this information so aims to develop a biofidelic method for testing the amount of deformation and level of force required to produce permanent injury to the dentition.

It is anticipated that the outcomes from this study could be applied to the development of a biofidelic test methodology to form the basis for a mouthguard test standard to be adopted around the world to assess and regulate the injury reducing potential of mouthguards to the teeth.

1.1 Research Problem and Focus

Mouthguard designs are currently being reassessed by the industry in an attempt to offer better protection to the jaw, TMJ and the brain, with little regard for the protection offered to the dentition. Additionally, the only currently available Australian Standard for the assessment of the protection offered by a mouthguard does not enforce the importance of preventing tooth injury, and falls short in allowing mouthguard designs to maximise injury reducing potential. The effectiveness of mouthguards in preventing dental injuries also appears to be poorly understood because the biomechanical characteristics of dentition and their responses to impacts and associated injury tolerance levels are not well defined.

Thus, the research problem addressed in this study is the development of experimental test methods to identify the response of the dentition to impact; in particular, the threshold at which injury occurs. The majority of research being performed on the biomechanical characteristics of dentition and their responses to impacts and associated injury tolerance level is being undertaken in the dental and orthodontic fields. As such, it focuses heavily on the replacement technology for restoration of teeth for aesthetic and mastication functionality. This study, however, seeks to help define impact injury tolerances. This information will allow for the major influencing factors on the extent of damage sustained by the dentition to be factored into the design of a test method to enable protection against such damaging factors.

1.2 Research Objectives

The primary aim of this research is to explore possible methods of investigating tooth injury biomechanics. To successfully do this, a detailed background on the dentition (the teeth and their supporting structures) must first be gathered. Typical injurious sporting impacts including speed, direction and location; and typical dental injuries and injury mechanisms must also be characterised.

Once this information is summarised, existing methods of investigating tooth biomechanics will be explored for relevance to impact injury biomechanics. The secondary aim of this study is to apply the knowledge gained to develop a method for testing the amount of deformation and level of force required to produce permanent injury to the dentition.

1.3 Research Outcomes and Application

The outcome of this study is the development of a method for testing the amount of deformation and level of force required to produce permanent injury to the dentition. This test methodology provides a way for injury tolerances of the dentition under direct impact loading to be investigated and defined. It is anticipated that this information could be applied to the development of a biofidelic surrogate jaw (inclusive of dentition) to use in a test methodology to assess the effectiveness of mouthguards in mitigating injury to the teeth and supporting structures. It is hoped that this could then be combined with the work currently being undertaken on MTBI to improve the mouthguard testing standards both in Australia, and internationally.

2. Background

The following background information on the dentition and mouthguard is presented to allow context to the more detailed information presented thereafter.

2.1 Dental Anatomy

Two major bones of the facial skeleton are the paired maxilla and the mandible, or, the upper and lower jaws [29]. The mandible and maxilla house the teeth in the alveolar part and process, more commonly known as the tooth sockets (Figure 1).

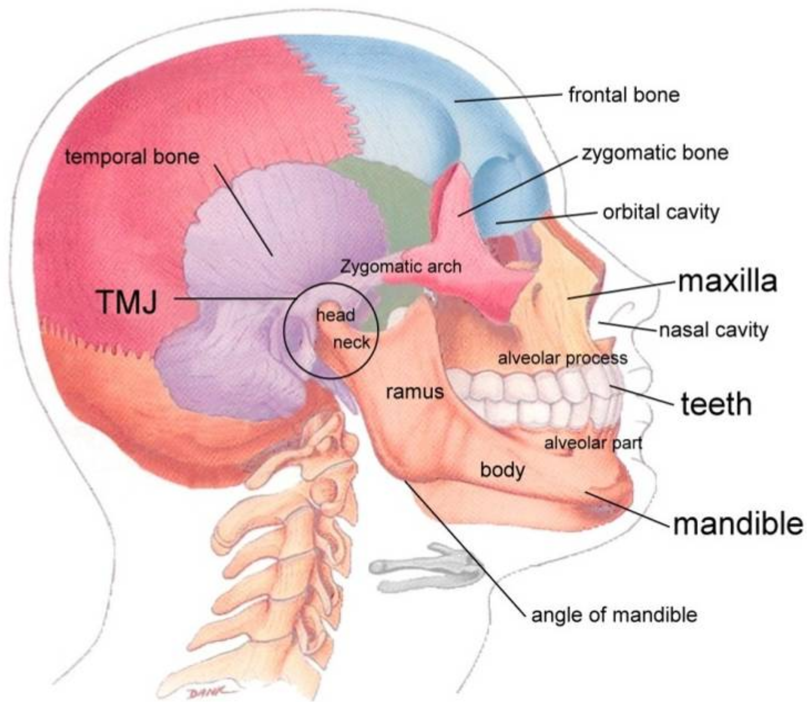

Figure 1 The Human skull and jaw, adapted from Moore [29].

Normally there are 32 permanent teeth, 16 in each jaw, including symmetrically on either side from front to back: two incisors, one canine, two premolars, two molars and one wisdom tooth. The World Dental Federation or FDI (Federation de dental Internationale) [30] uses a commonly accepted two digit notification method to help identify the teeth. The first number indicates the tooth's location (upper left or right, lower left or right) and the second number indicates the specific tooth (Figure 2) [30]. Incisor and canine teeth have lingual (tongue side) and labial (lip side) surfaces and incisal (cutting) edges. The premolar and molar teeth have buccal (cheek side), lingual and occlusal (chewing) surfaces. Tooth surfaces which face toward the mesial line are termed proximal, and those which face away are termed distal. The front teeth are termed anterior, and the back teeth are termed posterior.

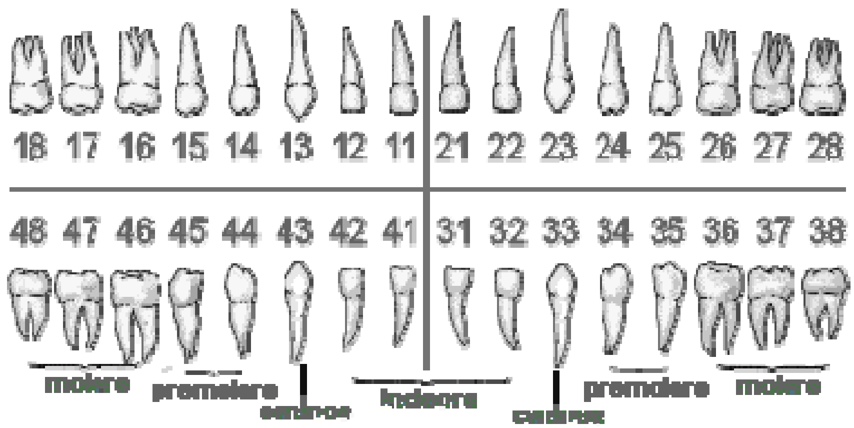

Figure 2 The permanent teeth, from www.fdiworldental.org [30].

Teeth have an inner pulp chamber surrounded by dentin, and have a hard, white enamel outer covering (Figure 3). Each tooth consists of three portions: the crown, projecting above the gingivae, more commonly known as the gums; the root, embedded in the alveolus of the mandible or maxilla; and the neck, the constricted portion between the crown and root.

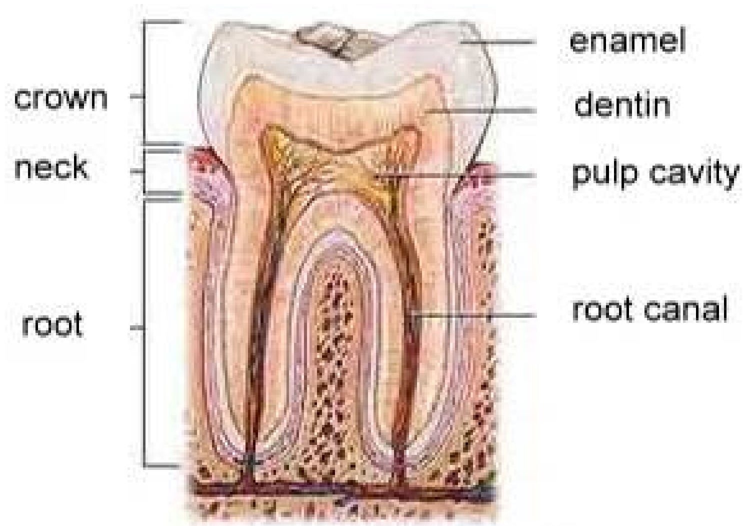

Figure 3 Example of a tooth with two roots, from www.adamimages.com [31].

The gingivae, or gums, are composed of fibrous tissue, which is covered with a mucous membrane. They are attached to the margins of the alveolar processes of the jaws and to the necks of the teeth. The root is held in the alveolus (socket) by a fibrous, periodontal membrane or ligament, more commonly known as the PDL [29]. The PDL is a thin layer of soft connective tissue consisting of densely packed collagen fibres [29, 32]. According to Arola and Reprogel (2006) [33] "*the tissue serves as an elastic foundation for the hard, outermost enamel, and as a protective enclosure for the central pulp*". The pulp cavity contains connective tissue, blood vessels and nerves and is continuous with the periodontal tissue through the root canal and the apical foramen [34, 35].

Table 1 shows the usual number of roots for each of the teeth, refer to Figure 2 [36].

Table 1 FDI tooth numbers, names and usual number of roots for each of the permanent teeth, from www.fdiworldental.org [36].

Tooth	**FDI Tooth Number**	**Number of roots**
Maxillary central incisor	11, 21	1
Mandibular central incisor	41, 31	1
Maxillary lateral incisor	12, 22	1
Mandibular lateral incisor	42, 32	1
Maxillary Canine	13, 23	1
Mandibular Canine	43, 33	1
Maxillary first premolar	14, 24	2
Mandibular first premolar	44, 34	1
Maxillary second premolar	15, 25	1
Mandibular second premolar	45, 35	1
Maxillary first molar	16, 26	3
Mandibular first molar	46, 36	2
Maxillary second molar	17, 27	3
Mandibular second molar	47, 37	2
Maxillary third molar	18, 28	3
Mandibular third molar	48, 38	2

Dentin is a hydrated hard tissue [33], composed of approximately 20% organic substance with type I collagen as the major component [35, 37, 38]. The remaining content is inorganic material and water [35, 37, 38]. Dentin structure more closely resembles bone than it does enamel, yet is slightly more calcified than bone (75% versus 65% mineral content by weight) [35]. Dentin is a structural unit traversed by a network of tubules that are oriented radially outward from the central pulp towards the dentin–enamel junction [33]. Both the tubule density and lumen diameter decreases within increasing distance from the pulp [33]. Dentin exhibits the largest elastic modulus in the direction perpendicular to the tubule axis [33]. According to Ni and Chen (2010), dentin is a stronger substance in tension than enamel [35].

The enamel is the hardest and most compact part of a tooth, with traces of fluoride of calcium, phosphate of magnesia and other salts [34]. The enamel also has a thin layer of cementum, which resembles bone in structure and chemical composition [34]. In a study performed by Tanaka and Fiholl in 2008 [38] it was determined that radiographically, the enamel of human teeth is more radio dense than cementum and dentin. The secondary role of the PDL is to transfer loads from the tooth to the mandible. According to the literature, PDL stiffness is much lower than those of the dentine and bone. Natali, Carnial and Pavan (2008) [32] attribute this to the PDL being the main cause of tooth short-term mobility. Furthermore, Natali et al. (2008) [32] suggest that the strain configuration of the PDL regulates the remodelling processes within the alveolar bone, thus the PDL also influences tooth long-term mobility, for example, when orthodontic loads are applied.

2.2 Dental Anthropometrics

A summary of normal adult male dental arch measurements of various researchers is provided in Table 2. Specific anatomical landmarks were used to determine the measurements (Figure 4).

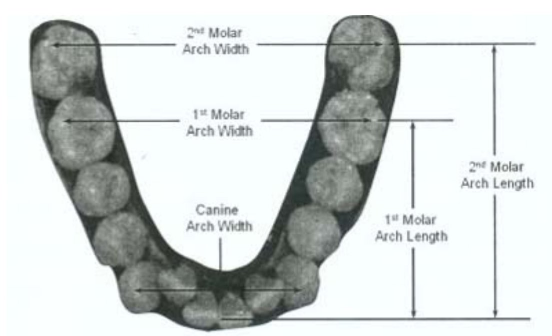

Figure 4 Image of the maxillary dentition and arch length/width measures, from Craig 2007 [27].

Table 2 Anthropometric measurements (in mm) of dental arches from a variety of sources.

			DeKock (1972) adult males [39]		Staley et al (1985) adult males [40]		Raberin et al (1993) adult males [41]		Bishara et al (1996) early adulthood male [42]		Braun et al. (1998) adults [43]		Uysal et al (2005) [44]		Craig (2007) [27]	
			N=16		N=16		N=159		N=15		N=15		N=72		N=16	
MEASUREMENTS (in mm)			Avg	Std Dev	Avg	Std Dev	Avg	Std Dev	Avg	Std Dev	Avg	Std Dev	Avg	Std Dev	Avg	Std Dev
width	canine	maxilla			36.2	2.3			34.4	2.1	34.0	2.3			33	4
	1st premolar								42.1	2.5						
	1st molar		59.6	2.3	54.7	2.1			50.7	3.7	53.6	2.8			52	4
	2nd molar												52.3	3.5	58	5
	Total										73.2	4.4				
length	1st molar		32.8	2.0												
	2nd molar												39.5	3.0	45	3
width	canine	mandible			26.3	1.8	26.1		25.9	1.7	25.2	1.8			28	2
	1st premolar								34.6	1.9						
	1st molar		55.9	1.8	53.1	1.6	46.0		45.7	2.8	46.0	3.0			51	3
	2nd molar						55.1						58.2	2.6	57	3
	Total										62.3	4.2				
length	1st molar		27.8	2.0												
	2nd molar						39.9						44.7	3.2	42	5

Recently, Brook et al. (2009) [45] compared permanent mesio-distal crown diameters between males from four ethnic groups, Southern Chinese, North Americans of European ancestry, modern British of European ancestry and Romano-British. Their findings are shown in Figure 5.

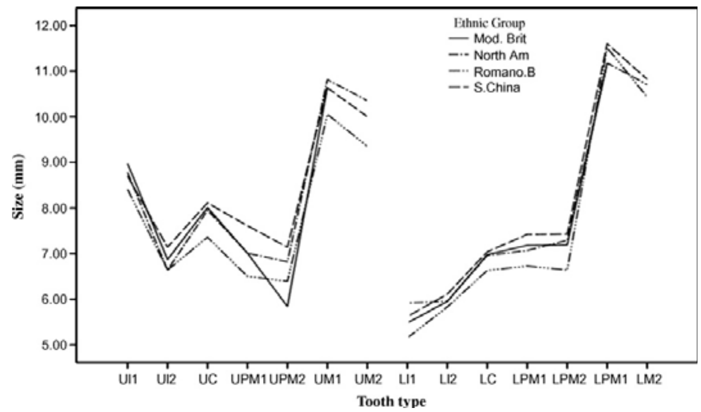

Figure 5 Comparison of mean tooth size per tooth type between different ethnic groups, from Brook et al 2009 [45] U= upper (maxilla), L= lower (mandible), I= incisor, C= canine, PM= premolar, M= molar.

Typical individual tooth sizes have been detailed by Myofunctional Research Co. (Helensvale, Australia) based on extensive dental cases [46]. The typical dimensions of an upper right central incisor (FDI tooth 11/21) and an upper right lateral incisor (FDI tooth 12/22) are shown in Figure 6 and Table 3.

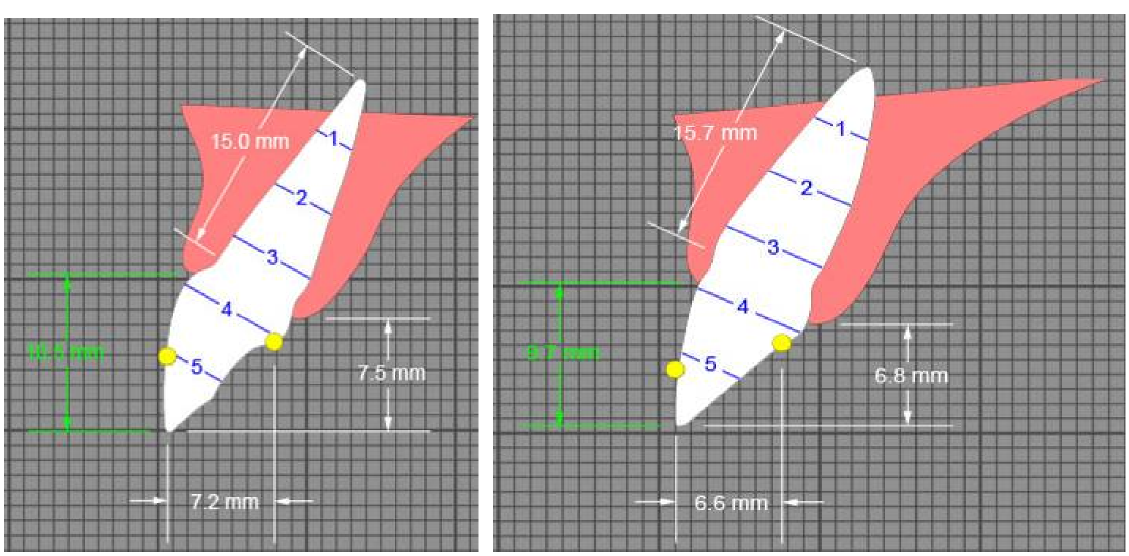

Figure 6 Dimensions of typical upper incisors (left) upper right central incisor (right) upper right lateral incisor, showing typical tooth dimensions, from Myofunctional Research Co [46].

Table 3 Dimensions of typical upper incisors, from Myofunctional Research Co [46], see Figure 6**.**

Ring Number	**Perimeter dimension**	
	Right central incisor	**Right lateral incisor**
1	7.7mm	9.7mm
2	12.9mm	14.3mm
3	17.4mm	17.2mm
4	21.9mm	19.0mm
5	22.8mm	19.7mm

2.3 Periodontal disease

Periodontal diseases are chronic inflammatory diseases that lead eventually to loss of the supporting structures of the teeth, including resorption of the alveolar bone of the jaw. Periodontal diseases are the most prevalent of the diseases of the bone in humans, being severe enough to lead to tooth loss in 10 to 15% of adults [47].

Periodontal disease can be associated with any periodontal tissue, whether it be the gingival alveolar, cementum or periodontal ligament. Periodontal disease is mainly caused by bacterial infection, and generally occurs when the borders between the teeth and gingivae are left unclean.

Periodontal disease spreads through the subgingival pockets which progresses apically as the infection destroys the soft tissue connection between the gingival and the tooth root (Figure 7). The alveolar bone resorbs, flattening the bone crest (horizontal bone loss) and widening the bony socket in which the tooth sits (vertical bone loss). As these processes continue the infection can lead to the destruction of the supportive structures that hold the teeth in place thus the tooth is left unsupported and may be lost [47]. As a consequence, severely progressed periodontal disease can result in bone loss, the loss of teeth and or significant destruction of the periodontal tissues.

Periodontal disease also increases with age, and a generalized decrease in bone density may contribute to susceptibility to alveolar bone loss [47].

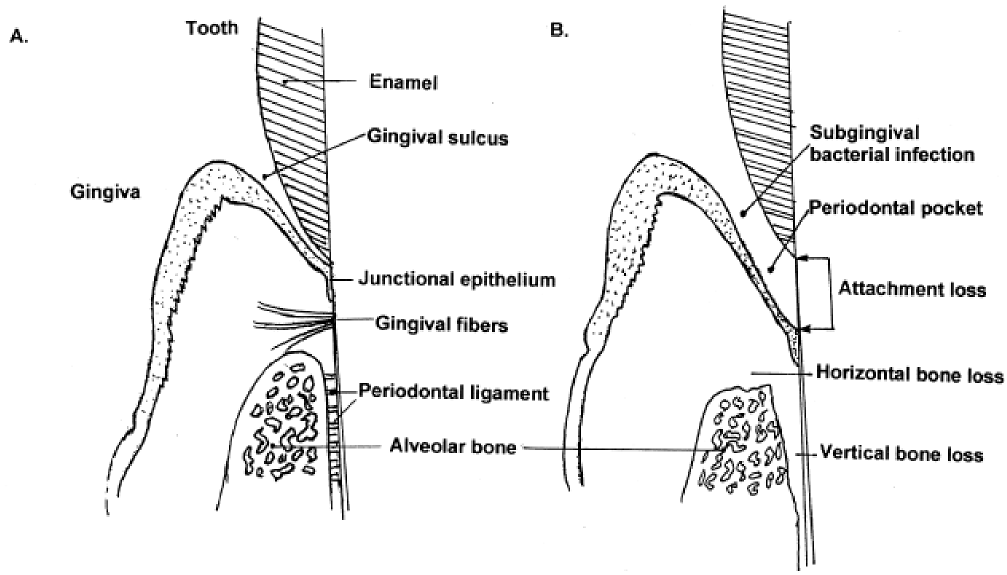

Figure 7 *The periodontium. A. In health, the alveolar bone crest comes within 1mm of the height of the cemento-enamel junction of the tooth. Gingival fibres connect the gingival soft tissue to the cementum of the tooth root, and periodontal ligament fibres connect the alveolar bone and cementum. B. In periodontal disease, Gram-negative bacterial infection occurs subgingivally. Soft tissue damage produces attachment loss and loss of the periodontal ligament fibres, deepening the sulcus into a periodontal pocket. Bone resorption lowers the height of the alveolar bone crest (horizontal bone loss) and moves the bone surface away from the tooth root (vertical bone loss)* Reproduced from Baker, 2000 [47].

2.4 Effects of Ageing on the Teeth

Several investigations have reported age related changes in the pulp–dentin complex of human teeth [48]. The changes can be physiological, related to normal stresses, and also pathological, a result of cavities, tooth surface loss, or restorative treatment [48].

In a study performed by Ni and Chen (2010) [48], age-related tooth quality *in vitro* was assessed by quantifying changes in dentin and pulp simultaneously using the NMR relaxation technique. Eight third molars clinically extracted with the ages from 17 to 67 years old were collected from the University of Texas Health Science Centre at San Antonio, UTHSCSA. Their findings were as follows: *"Comparing the old tooth to young tooth, the volume fraction of larger pore size (pulp) is significantly reduced for the older tooth, since the volume fraction of the median and small-diameter pores is increased due to age-related changes. ... It is found that the intensity* *ratio of dentin to pulp sensitively changes from 0.48 to 3.2 approaching a linear growth with age".*

Palti, Machado, da Silva, Abdo and Lima [49] evaluated the superficial microhardness of enamel in teeth at different post-eruptive ages. Their results demonstrated "*that superficial microhardness values have a tendency to increase over the years, with statistically significant difference only between un-erupted enamel and that with more than 10 years after eruption. According to the present conditions and methodology, it was concluded that there were differences between the superficial micro-hardness of specimens at different eruptive ages, revealing an increasing mineralization*".

Koester, Ager and Ritchie (2008) [50] also assessed teeth at progressing development stages. They found that in contrast to bone, there is no remodelling after tooth growth is complete. "*During aging, human dentin sclerosis causes the tubes to become occluded through reposition of carbonated apatite, leading to transparency to visual line of the dentin (termed "transparent" dentin). This leads to changes in the mechanical properties, most notably a loss in ductility, toughness and cyclic fatigue resistance*."

In addition to the lack of structural integrity of dentin and enamel seen in aged teeth, other common issues include osteoporosis, early decay, micro stress fractures and micro-leakage.

2.5 Oral Health Statistics of the Aged Australian Population

Dental caries (tooth decay) is Australia's most prevalent health problem, edentulism the third most prevalent, and periodontal disease the fifth most prevalent [51]. Caries and periodontal disease account for 90 percent of all tooth loss [52].

An extract from the Australian National Oral Health Plan 2004-2013 [53] states the following about oral health of the aging population:
"While adults are experiencing less decay than they did in the 1970s, they have more untreated caries and more filled teeth Many Australian adults—especially in older age groups—have lost enough natural teeth to have a substantial effect on their oral functioning, particularly chewing and therefore diet and nutrition. Older people—an increasing population group—are,

nevertheless, retaining more of their natural teeth for longer, and this healthy trend brings with it a substantial increase in the risk of tooth decay"

During 2004-2006 1413 and 5505 Australian adults aged 15-97 were interviewed and examined respectively as part of the National Survey of Oral Health [54]. The results showed the following findings:

- *Approximately 1-in-20 Australian adults (6.4%) had lost all their natural teeth.*
- *Among the 93.6% who were dentate (that is, people who had one or more natural teeth), an average of 4.5 teeth per person had been extracted because of dental decay or gum disease, leaving 11.4% of people with an inadequate natural dentition, defined as fewer than 21 teeth.*
- *Generations born in the first half of the twentieth century had profoundly greater levels of tooth loss and tooth replacement than more recent generations.*
- *Experience of dental decay was ubiquitous within the adult population. Over 95% of people born before 1970 had some experience of dental decay, and the figure dropped only to 76% among people in the most recent generation, born 1970–90. The average number of teeth affected by decay per person ranged from 4.5 in the 1970–90 generation to 24.3 in the pre-1930 generation.*
- *6.7% of Australian adults had untreated decay on exposed root surfaces, a condition that was much more frequent in the pre-1930 generation (17.3%) than the 1970–90 generation (1.6%).*
- *Untreated decay was more frequent among males.*
- *Approximately one in five Australian adults had moderate (20.5% of people) or severe (2.4% of people) gum disease, also called 'periodontitis'.*
- *Periodontitis was strongly associated with age, occurring among 60.8% of people aged ≥75 years. Yet even in that age group, signs of periodontitis were found in only one or two anatomical sites around the mouth, on average, from among the 84 sites measured per person.*
- *Periodontitis occurred more frequently among males.*
- *One in five Australian adults (19.7%) additionally had signs of gum inflammation (redness, swelling or bleeding).*
- *There were 25.9% of Australian adults who had wear visible on their lower front incisor teeth, to the extent that it had worn through the tooth's hard, enamel edge. More severe*

wear was observed among 3.3% of adults in whom at least half of the height of the lower incisors had worn away. This severe level of wear was much more frequent in the pre-1930 generation (12.0%) than the 1970–90 generation (0.5%).

- *Severe wear of one or more lower incisors was three times more likely among males compared with females.*

2.6 Mouthguards and Current Protection Standards

Most mouthguards are worn on the upper jaw, with the anterior teeth and gums covered [6]. The guard also covers the biting surfaces of the upper teeth, and extends slightly on to the palate. It is held in place by a close fit to the teeth and by upwards pressure of the lower jaw [6].

Mouthguards are commonly worn in sporting events where there is a serious risk of a blow to the mouth or jaw area, and are increasingly becoming a safety requirement of the game. In sports for which the regulatory authorities have made mouth protection mandatory, dental injuries have been reported to be reduced by 60% and soft tissue mouth injuries by over 80% [6]. Acting as a shock absorber, mouthguards are generally considered to reduce the likelihood of injury by providing adequate protection. The protective capabilities of mouthguards against TMJ injury and mild traumatic brain injury MTBI, or more commonly concussion, have been studied in detail and continue to be topical issues in today's research.

Mouthguards are hypothesised to be able to reduce the likelihood of orofacial injuries through several mechanisms. These mechanisms can be classified in terms of the benefits gained during an impact to the maxillo-facial region including the following [8, 55, 56]:

- separation of the maxillo elements – preventing fractures, chips and dislocations of the teeth,
- separation of the teeth from the soft tissues of the mouth – preventing lacerations of the lips, gums, inner cheeks and chin, and bruising of the soft tissues [55, 57],
- separation and stabilisation of the jaw - reducing the risk of fracture in the mandibular condyles and damage to the TMJ [55, 56, 58-60], (Figure 8) [61], and
- absorption and dissipation of the forces sustained – preventing and or reducing MTBI and impact on the skull [60].

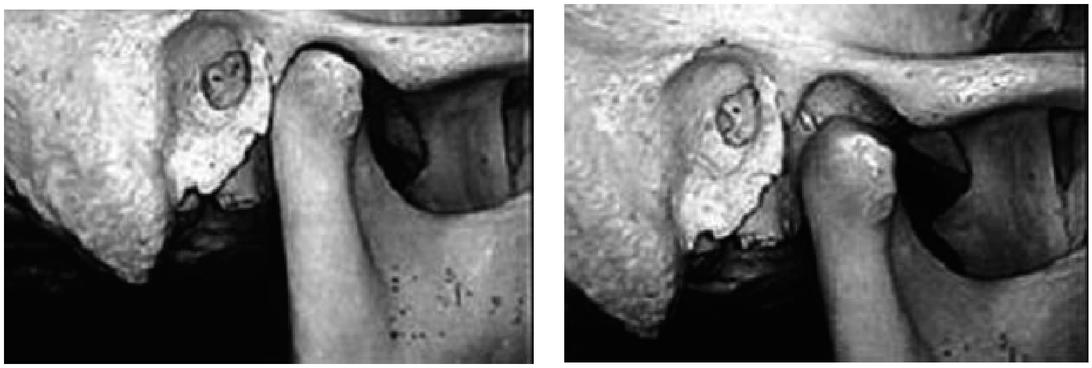

Figure 8 Position of the condyle without (left) and with (right) mouthguard, from Waliko 2004 [61].

Information on the injuries that do still occur, however, is often gathered as a by-product of studies looking at the more serious head injuries. As such, it is unknown in all these cases what level of involvement the mouthguard had in the dental injuries seen, for example, are the mouthguards simply not protecting against the level of force delivered in the impact, or is there an issue with retention of the mouthguard during an impact?

The few researchers who are assessing ways to reduce the occurrence of dental injuries in sporting activities suggest that to improve a mouthguard the material must be improved to handle the impact loads [1, 55, 62]. They also highlight, however, that there is little data available on the injury tolerance levels of the teeth and thus what force levels the mouthguards should protect against.

2.6.1 Current Protection Standards

Currently the protection offered by mouthguards available in Australia is regulated by a Guideline Handbook produced by Standards Australia, **HB 209-2003 Guidelines for the fabrication, use and maintenance of Sports Mouthguards, Standards Australia 2003,** which merely places criteria on the mouthguard’s material properties, including:

- Hardness of Shore A at 37^{o}C, liner 40 to 60, shell 55 to 85.
- Water absorption at 37^{o}C of less than 0.5%.
- Force transmitted should not be more than 30% of force delivered (performed at room temperature).
- Tear strength at 37^{o}C not less than 200N/mm.

The following International standards relate to the testing of materials used in sports mouthguards:

- ASTM F697-00. Standard practice for care and use of mouthguards. 2006.
- ASTM F748-06 Standard Practice for Selecting Generic Biological Test Methods for Materials and Devices.
- ISO 7405 Dentistry – Preclinical evaluation of biocompatibility of medical devices used in dentistry – Test methods for dental materials 1998.
- ISO 10993-1 Biological evaluation of medical devices Part 1- Evaluation and testing 2003 (Equivalent to AS ISO 10993.1 2002).

A more comprehensive regulation is offered by a European Standard, **DD 253:2001 Mouthguards for the use in sport and recreation – requirements for test methods.** This regulation was confirmed in December 2007. The required mechanical properties of mouthguards in DD 253:2001 Mouthguards for the use in sport and recreation are shown in Appendix B.

The requirements of the Australian Handbook are compared with the requirements of the European Standard in

Table 4.

Table 4 Summary of the types of test requirements in the Standards Australia (SA) guidelines and the British Standards Institute (BSI) development document for mouthguard testing and requirements.

	Document	**Test method**	**Mouthguard property**		**Parameter**	**Requirement**
SA	209-2003		material	Liner Hardness	Shore A at 37^{o}C	40 to 60
SA	209-2003		material	Shell Hardness	Shore A at 37^{o}C	55 to 85
SA	209-2003		material	water absorption	37^{o}C	less than 0.5%
SA	209-2003		material	amount of impact absorbed	room temperature	70%
SA	209-2003		material	tear strength	37^{o}C	200N/mm
BSI	DD 253:2001	4.5 5.5.2	design	mouthguard fit	Mouthguard on jaw cast. Pull test: force applied at 90±10º in the plane of the occlusal plates, to the edge of the lingual flange between the central incisors.	minimum 1N
BSI	DD 253:2001		design	Size/coverage	Maximum and minimum values for Protection and comfort	
BSI	DD 253:2001	4.6 5.6	material	force transmittance	Impact with anvil radius 35±0.5mm mass 2500±100g face central flat region >30mm (diameter)	3kN
BSI	DD 253:2001	4.8 5.8	construction	pull apart	draw ends of labial flanges apart at 50±25mm/min	minimum 200N
BSI	DD 253:2001	4.9 5.9	construction	peel strength	Separate layers of mouthguard at 100±20 mm/min	Minimum 4N/mm

3. Literature Review of Tooth Injuries

Recently, due to the work being performed on MTBI and jaw injury, more complex mouthguard designs are being explored, with a number of new models becoming available to the general public. These include linked and unlinked ‘double’ mouthguards (covering both the upper and lower teeth) and mouthguards of double layer materials to help absorb impact forces.

In mouthguard design, consideration must be given to the nature of the collision, for example whether the collision involves an impact with hard or soft objects, the speed and acceleration of the impact and the size and mass of the impacting object; the characteristics of the mouth, for example the brittleness of incisors, the strength and stiffness of the teeth and periodontal ligaments holding the teeth in place, the rugged occlusal surfaces of the molars, the soft gingival; the geometry of the mouth; and the biocompatibility of the materials used [55].

Most importantly, mouthguards are required to provide adequate protective capabilities to the teeth, mouth and jaw, thus mouthguard properties including shock absorbing capabilities, hardness, stiffness, tear strength, tensile strength and water absorption must be considered in detail. These material properties have been discussed, evaluated and tested throughout the literature, however, such tests are always performed as a materials test of the unformed mouthguard material. It is again highlighted, that although the mouthguard material properties are assessed for their force reduction properties, this has not been directly related to the injury tolerance level of the teeth thus the true injury reduction potential of mouthguards remains under defined.

To determine the best approach to developing a method for investigating the biomechanics of the teeth, a thorough literature review was conducted to gather all known information regarding tooth injures in sport, and to collect any known information about tooth biomechanics, and to assess existing equipment and measurement technologies.

The information found and its significance is reviewed critically below in relation to the aim of this study.

3.1 Characteristics of Sporting Impacts to the Dentition

The Australian Dental Association (ADA) and many published authors [1-5], have identified sporting activities as one of the principal causes of cranio-maxillofacial injuries, with approximately 20% of sports related hospitalisations each year involving principal injuries to the head region. The literature suggests that sporting accidents are the cause of between 3% and nearly one third of all dental injuries reported each year [3, 6, 10, 62].

The most common maxillofacial injuries in sports are injuries to the dentition and soft tissues of the head and face, followed by facial fractures, followed by skull and brain injuries (mainly concussion), and TMJ injuries [3, 5, 6, 9, 10]. Often, an impact collision results in more than one of these types of injuries, and rarely are dental injuries seen on their own. Although not the most common, skull, brain and TMJ injuries receive the most attention in the literature due to their more serious and permanent nature.

Important factors in the injury outcome as a result of sporting impacts are the teeth impacted most often, the location, direction, and force of the impacts as well as the size and mass of the impacting object. Although much is discussed in the literature regarding impact types and their injury outcome, the majority of the research has concentrated on injury outcome to the TMJ and brain, focussing on Mild Traumatic Brain Injury (MTBI). Little is specific to injuries to the dentition. What is known however has been summarised below.

3.1.1 Teeth involved

The literature mainly reports that the maxillary central and lateral incisors (tooth numbers 12, 11, 21 and 22 in Figure 2) constitute the majority of injury cases to the teeth [9, 63-65]. Prabhakar, Jurthukoti and Kayalvizki (2007) [65] report that crown fractures or chips of permanent incisors represent 18-22% of all traumas to the dental hard tissue; of these, 96% involve maxillary incisors (80% central incisors and 16% lateral incisors). This information confirms the importance of mouthguards in providing coverage and protection to these upper front teeth, and justifies concentrating efforts on investigating tooth biomechanics to these single root, cuspid teeth.

3.1.2 Impact Locations

Various studies of impacts during sporting activities reveal that cranio-maxillofacial injuries are due to four main impact mechanisms:

- Frontal impacts, to the face, forehead, mandible central maxillary incisor (CMI),
- rear impacts, to the back of the head,
- side impacts, to the side of the head and the jaw, and
- uppercut type impacts, to the mandible [3, 9, 11, 12].

One of the most comprehensive studies on sporting impacts to the head was performed as a series by Andersen and co-workers (2004) [9], who found that the point of impact on the head was the face (including the mandible) in 57% of the cases, the back of the head in 22%, the side of the head in 13%, and the forehead in 6%.

3.1.3 Impact Directions

Although it is pertinent to assume that a direct frontal impact to the tooth may result in injury, and commonly supported as such in the literature [59, 60, 66], Found, Patrick and Pearson (2006) [11] suggest that uppercut type loading to the mandible also results in injury to the teeth, with the bottom teeth compressing the upper teeth to produce principal stress directions in the longitudinal direction and perpendicular to it, to produce a compressive shear failure, resulting in chips occurring at both corners of the front teeth (Figure 9). This is supported by other literature including an earlier study performed by Biasca, Wirth and Tegner (2002) [67]. It is noticed that uppercut impacts are being more prominently included in recent studies on head impacts, particularly those in the sporting field.

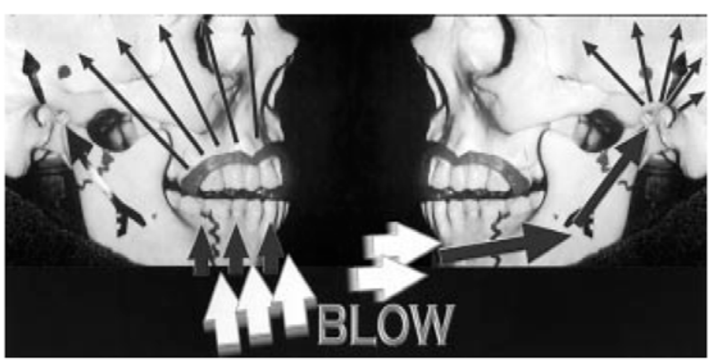

Figure 9 Transmission of forces from mandible impacts, from Biasca et al (2002) [67] (Left) Inferior/uppercut impact to the mandible (right) Anterior/frontal impact to the mandible.

3.1.4 Impacting Objects

Studies have linked the severity of the resulting injury to the impacting object, generally with correlation between the size of the impacting surface and mass of the impacting object [3, 12]. Cummins and Spears (2002) [12] describe this phenomenon as follows: *"hard-object collisions in sport usually occur with objects of low-mass, such as base balls. Although peak force can reach high levels, it is likely to be short in duration. In such cases, stresses concentrate around the point of impact, without dissipating into the structure. Understandably, it has been suggested that hard-object collisions are more likely to initiate fracture in impact zones. In contrast, collisions with soft objects usually involve a heavy opponent and, although the magnitude of peak force may be less than for hard-objects, the period of force is substantially longer in this situation. Stress is dissipated into the tooth-bone complex, concentrating in regions other than the impact site. Such collisions are more likely to cause fracture away from the impact zone. In short, the process of fracture initiation is likely to differ depending on the colliding object"*.

Direct frontal and uppercut impacts occur in sporting activities as a result of the following summarised reasons, (Figure 10) [5, 6, 9, 13-15]:

- direct impacts with sporting equipment,
- direct impacts with other players body regions, including heads, elbows, knees and or boots,
- direct impacts with the ground or playing surface,
- direct impacts with other objects, such as goal posts, sideline advertisements, or
- indirect impact through the teeth clashing together as a result of objects striking the lower jaw.

Figure 10 Compilation of sporting related head impacts, from Andersen et al. (2004) [9].

3.1.5 Impact Forces

Many authors have documented the speeds and accelerations of injurious impacts seen in sporting activities, either from collisions with sporting equipment or other players body parts [2, 15, 16, 18, 68]. Although these injurious impacts are once again concentrated on head, brain and TMJ injury, they can be used as an indication of the level of force delivered in an impact to the dentition.

A kicked soccer ball has been reported by many authors to travel at speeds of 1-36m/s (3-129km/hr), however most head to ball impacts occur at ball speeds less than 18m/s (65km/hr) [2, 15-17]. Head accelerations experienced in such ball headings are reported to range between 1.7 and 8.8g (mean 3.7 SD 1.3g) [16]. Naunheim and co-workers (2003) [17] report that for ball speeds of 9 and 12 m/s, head accelerations were found to be 158 SD 19m/s^2 (~16g) and 199 SD 27m/s^2 (~20g) respectively.

Withnall and Shewchenko (2005) [18] performed a study whereby game video of 62 cases of head impacts (provided by the FIFA Medical and Research Centre, F-MARC) were analysed to reveal the typical impact configurations and representative impact speeds. The impacts were then re-enacted in the laboratory by volunteer football players and instrumented Hybrid III pedestrian model crash test manikins. The results of their study concluded that elbow to head impacts occurred at speeds of 1.7-4.6m/s with an overall mean of 3.02m/s, lateral hand strikes to the head occurred at speeds of 5.2-9.3m/s with an overall mean of 7.67m/s and head to head impacts occurred at speeds of 1.5-3.0m/s.

A field study performed by Guskiewicz and co-workers (2007) [19], which embedded accelerometers in the helmets of collegiate football players, recorded linear accelerations ranging in impact magnitudes of 60g to 168g during various head impacts.

Schnebel and co-workers (2007) [20] also instrumented the helmets of university and high school footballers to record head impact accelerations. Their results show that college and high school footballers sustained high-level impacts greater than 98g. Duma and co-workers (2005) [21] also instrumented the helmets of collegiate footballers, and recorded peak head accelerations of 32 SD 25g during non-injurious head impacts. One concussive head impact was observed with a recorded peak acceleration of 81g.

By reconstructing helmet to helmet impacts using Hybrid III dummies, Viano, Casson and Pellman measured acceleration in both heads involved in head to head impact collisions in professional football matches on two separate occasions. In 2005 [22], concussive impacts were simulated to determine how the striking player delivered the concussive blow. They found mean head acceleration levels of 46.8 SD 21.7g in the striking player. In 2007 [23], they found the impact response of the struck concussed player's head included peak accelerations of 94 SD 28g.

Waliko, Viano and Bir (2005) [24] investigated head and brain injury for boxing punches aimed straight at the lower third of the face of a Hybrid III dummy. Seven Olympic boxers from five weight classes delivered 18 straight punches to the frangible faced dummy, which were later analysed to reveal that a punch force averaged 3427 SD 811N, hand velocity 9.14 SD 2.06m/s, and effective punch mass 2.9 SD 2.0kg. The jaw load experienced under such punches was found to be 876 SD 288N.

Takeda and co-workers (2005) [25] evaluated the distortion to the mandible and the acceleration of the head from an uppercut to the mandible. Using a pendulum device with a steel ball weighing approximately 300g, an acrylic resin plate fixed to the left second premolar of the mandibular bone of an artificial skull model was impacted. The impacting acceleration of 210.2g was dissipated through the parietal, temporal and frontal regions as follows; the acceleration of the parietal region was 58.8g, the temporal region was 23.2g, and the frontal region was 128.2g.

As mentioned earlier, the majority of this research is concentrated on assessing how the direction, speed, acceleration, impactor size and or mass affect the injury outcome of the brain. A big area of debate in the research about head impact and the resulting head injury is the level of rotational acceleration experienced, in addition to the above mentioned linear accelerations, and rotation of the neck and its involvement in head injury. It remains unexplored in detail in the literature what affect these impact characteristics have on injury outcome of the dentition.

3.1.6 Summary

In summary the literature indicates that a sporting impact injurious to the dentition will occur either directly to the frontal surface of the tooth, or indirectly to the incisal (cutting) edge of the tooth, most commonly to the maxillary central and lateral incisors. It is indicated, but not definitively stated that these injurious impacts are associated with either impacting speeds of 2-20m/s, or resulting head acceleration levels of above 80g. It is also indicated in more general investigations that the impacting object affects the type of injury. In summary the literature suggests that hard, low mass objects (i.e. balls) impact over a short duration and incur visually obvious damage to the crown of the tooth at the point of impact; while softer, heavier objects (i.e. body parts) occur over a longer duration thus dissipate injury to regions away from the impact site.

Based on this literature an assessment can be made of the force characteristics an impacting object delivers to the maxillofacial region, but this still does not lead to understanding what the tooth experiences or what the resulting motion of the tooth is. To understand better the implications of injury at the impact site as opposed to injury away from the impact site an exploration of dental injury mechanisms must be undertaken.

3.2 Dental Injury Mechanisms

Physical injury will occur when the biomechanical response of the dentition results in deformation beyond a tolerable limit resulting in damage to anatomical structures.

Generally speaking, permanent dental injuries can be classified as follows [11, 25, 67, 69-74], (Figure 11);

- chipped teeth,
- tooth fractures, of either the root or crown,
- tooth dislocations or displacements including luxation, intrusion and avulsion, and
- trauma to the structure supporting the tooth in the alveolar socket.

Tooth concussions have also been reported in the literature whereby the tooth is traumatized but not moved out of its position [67].

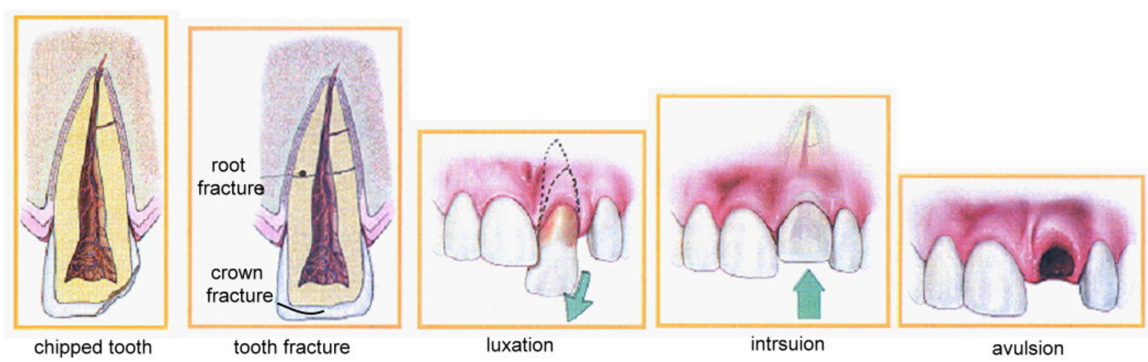

Figure 11 Dental injuries, from www.adamimages.com [31].

The majority of these injuries are to the exposed section of the tooth and thus are visually evident to the naked eye when assessing the dentition for signs of injury. Injuries to the supporting structures or root of the teeth however are more difficult to assess with the naked eye yet are just as responsible for permanent damage to a tooth. The following review touches on the complexity of injury to the tooth's supporting structures.

Root fractures of the incisors were assessed by Welbury and coworkers (2002) [75], who found that often root fractures were associated with a loss of pulp vitality, with poor tooth survival outcome when fractures occurred in the gingival third region.

Vinckier and co-workers (1998) [76] studied injuries to human teeth and report the most frequent permanent complications with tooth ‘concussion’ or subluxation are pulp necrosis and obliteration of pulpal tissues, which can cause tooth death. They state that luxation often is associated with hidden damage to the pulpal tissues and PDL, and in the more severe cases can also involve damage to the alveolar bone. Vinckier et al. state similar complications occur with intruded teeth, and avulsion injuries also often involve disruption to the pulpal tissues and PDL.

Andreasen, Backland and Andreasen (2006) [63, 64] performed a prospective study of 140 intruded permanent teeth to evaluate healing complications. Their study describes the nature of intrusion injuries as those “*in which all soft tissue and some hard tissue components are damaged i.e. gingival tissues, periodontal ligament, alveolar bone and the pulp*”. Their findings are generally consistent with Vinckier and co-workers (1998) [76].

Andreasen et al. (2006) [63, 64] define the mechanism of intrusion to a more detailed level, explaining “*At the moment of impact, a significant amount of energy is spent to drive the tooth into its socket. In the gingival area, shearing stress will sever the gingival fibres, and compressive forces in the infra-bony part of the PDL will compress and sever the PDL and crush the alveolar socket wall. Furthermore, the tissues in the apical foramen area will be severed, and in the case of teeth with open apexes, the socket bone will possibly be pressed into the apical opening”*.

From this information, it appears that a way to visualise the damage to the hidden portion of the dentition, i.e. the supporting structures, is imperative in assessing the relation between an impact and its resulting injury to the tooth. It is important to understand the mechanism of an injury to the dentition when considering a method of investigating tooth injury biomechanics, as a way of observing, monitoring, defining and or quantifying the damage sustained must be factored into the test method.

3.3 Known Injury Tolerance Levels

In the two sections above, it has been established that for permanent injury to occur to a tooth, a load must either be applied directly to the exposed section of the tooth, imparting a force great enough to crack, chip, fracture or severely concuss a tooth, or, must be transmitted through the tooth to the supporting structures causing deflection of the tooth to such an extent that the tooth is severely displaced within its socket resulting in tooth death.

Thus the biomechanical response of the dentition can be considered in terms of the tolerance to a load transmitted through the tooth, i.e. the “tooth strength”; and the tolerance of the supporting structures to motion, i.e. “tooth compliance”. When considering tooth compliance (mm/N), which in turn is the inverse of tooth stiffness (N/mm), we are interested in tooth movement relative to the maxilla, as injury to the dentition occurs if the loading is sufficient to disrupt the fixation of support of the tooth in its socket, thus deforming the ligament or roots.

Although little information is available in the sporting impact and injury literature regarding the injury tolerance of the dentition, a greater degree of work has been undertaken in the dental and orthodontic areas. A large focus of dental and orthodontic research is in the defining of tooth mechanical properties to restore damaged teeth, allowing for desired aesthetic properties and adequate functionality, mainly in terms of mastication. The relevant findings are discussed below.

3.3.1 Tooth strength

Studies on the strength of teeth have been undertaken in an attempt to assess the level of force required to produce fracture and chipping type injuries. The most relevant studies are outlined as follows.

In 1976 Rasmussen and co-workers [77] investigated the fracture properties of excised samples of human enamel and dentin under distilled water at 26C^{o} by coupling work done on fracture measurements with a fractographic study that used scanning electron microscopy (SEM). Specimens were subjected to three-point bending until fracture using a test machine applying a constant strain rate. The total work required to fracture a specimen was determined from load vs. extension curves. Grooving of the specimens was required to ensure controlled fracture and fracture path. The average work of fracture for different directions was: for perpendicular dentin specimens, 270J/m^2; for parallel dentin specimens, 550J/m^2; for perpendicular enamel specimens, 200J/m^2; and for parallel enamel specimens, 13J/m^2.

In 1995 Patel and Burke [78] assessed the compressive strengths of foods and sweets which are associated with tooth fracture in vivo. Compressive forces of 0.16KN to 2.2KN were obtained for food items implicated in tooth fractures.

Lertchirakarn, Palamara and Messer (2003) [79] developed a finite element analysis (FEA) model to measure strain and loads at fracture of incisors. In their experimental validation of the model, excised maxillary and mandibular incisors were instrumented with strain gauges between the apical third and middle third of the root. Each root was subjected to an increasing force applied within the root canal space until fracture occurred (Figure 12). Partial or complete fractures of the incisors were noted in the bucco-palatal direction or bucco-lingual direction (Figure 13). The load and strain measurements are shown in Table 5 and Table 6 [79]. These findings (converted to N in the table) indicate maxillary incisor fractures occur under loads of 120-211N, which are consistent with the findings of Patel and Burke [78]. It was not clear in the study how load was applied, for example whether or not the canal was pressurised.

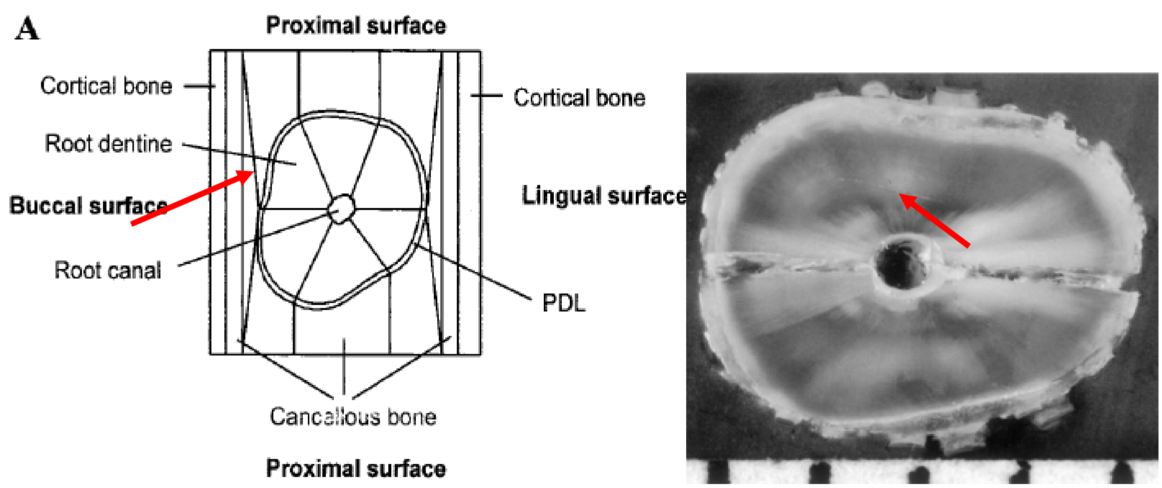

Figure 12 (left) Cross section through the maxillary incisor root model at the 10mm level. Note the root canal space in which the force was applied (arrowed). (right) Experimentally fractured maxillary central incisor, showing cross section 4mm from the root apex. Note the root canal space in which the force was applied (arrowed), from Lertchirakarn and co-workers (2003) [79].

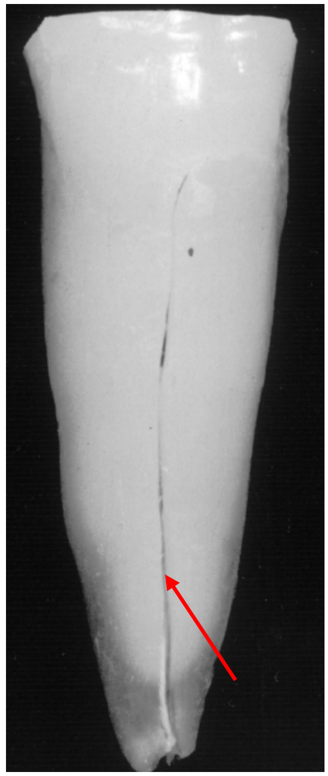

Figure 13 Experimentally fractured maxillary central incisor, showing bucco lingual root fracture, from Lertchirakarn and co-workers (2003) [79].

Table 5 Load and strain measurements at different sites on the root surface of five maxillary incisors loaded to fracture, from Lertchirakarn and co-workers (2003) [79].

Tooth number	**Strain on root surface (μ strain) T= tension C= compression**				**Load at fracture (kg)**
	buccal	palatal	mesial	distal	
1	254 T	89 T	2893 T	2507 T	21.5 *(211N)*
2	76 T	140 T	1800 T	1492 T	20.7 *(203N)*
3	254 C	204 C	1169 T	1620 T	14.5 (*142N)*
4	229 C	324 C	951 T	607 T	12.2 *(120N)*
5	159 C	102 C	874 T	771 T	12.4 *(122N)*

Table 6 Load and strain measurements at different sites on the root surface of five mandibular incisors loaded to fracture, from Lertchirakarn and co-workers (2003) [79].

Tooth number	Strain on root surface (μ strain) T= tension C= compression				Load at fracture (kg)
	buccal	palatal	mesial	distal	
1	471 C	199 C	1786 T	3233 T	8.6 *(84N)*
2	293 C	547 C	1973 T	694 T	7.0 *(69N)*
3	751 C	3894 C	3548 T	11608 T	6.2 *(61N)*
4	204 C	357 C	360 T	1118 T	6.7 *(66N)*
5	293 C	211 C	462 T	546 T	8.8 *(86N)*

Arola and Reprogel (2006) [33] experimentally evaluated the effects of tubule orientation on the mechanical behaviour of human dentin. 83 rectangular beam sections of coronial dentin from molars were loaded under quasi-static four-point flexure until failure. According to Arola and Reprogel what is known about tooth strength is that both the ultimate tensile strength (UTS) and shear strength of dentin are dependent on the tubule orientation. "*For dentin the work of fracture was lowest when the dentil tubules were oriented perpendicular to the plane of fracture. Similarly, the fracture toughness of dentin has been found to be largest when the crack is oriented parallel to the dentin tubules and consistent with the plane of fracture. In this orientation the collagen fibrils are perpendicular to the direction of crack extension and could be perceived as the critical structural element responsible for the dissipation of fracture energy"* [33].

They also summarise that the strength of dentin is also dependent on the anatomical location [33]. In general, the strength increases with distance from the pulp and the strength of coronal dentin (dentin in the crown of the tooth) exceeds that of the root dentin (dentin in the root of the tooth, Figure 3) [33].

Prabhakar, Jurthukoti and Kayalvizki (2007) [65] investigated the impact strength of reattached fractured anterior teeth in comparison to control, intact teeth. Fifteen excised human maxillary permanent central incisors were selected for the control group. Specimens were either fractured transversely to the long axis of the tooth, or embedded in an acrylic block with the tooth axis perpendicular to a pendulum which impacted the tooth. The results indicate intact teeth have a mean fracture toughness of 13.52kJ/m^2, which was higher than the values for the repaired teeth.

In 2008 Palti and co-workers [49] investigated the mineral content of tooth specimens by performing microhardness tests. The microhardness of the specimens was measured with a microhardness tester and a Knoop diamond indenter, under a static load of 25g applied for 5 seconds. Specimens were 3x3mm fragments of the flattest central portion of the crown of the tooth, and were flattened and polished in order to obtain a flat surface parallel to the base to perform the testing. The values of superficial microhardness found in human enamel were given as Knoop hardness numbers (KHN). Specimens with more than 10 years of eruption had a mean KHN of approximately 390, with a standard deviation of approximately 12.

3.3.2 Tooth Compliance

Studies on the displacement of the teeth under load have been undertaken mainly to aid in the design and outcome of orthodontic devices. The study of tooth displacement following the application of orthodontic loading regimes has shown the importance of several and complex parameters such as material properties of periodontal tissues, shape and length of tooth, width of the PDL, and the marginal bone level [80, 81], on the biomechanical performance of the tooth. The most important factor of the research is the highlighting of the importance of the PDL to the biomechanical performance of the tooth [81]. The most relevant studies are outlined as follows.

Back in 1981 [82] Atmaram and Mohammed estimated the physiologic stresses with a natural tooth considering a fibrous PDL structure through an FEA model. The elastic parameters used in their FEA model were obtained from even earlier literature [83-86], and are shown in Table 7.

Table 7 Elastic parameters of different materials used in Atmaram and Mohammed's FEA model [82].

TABLE
ELASTIC PARAMETERS OF DIFFERENT MATERIALS USED IN FEA MODELS

Material	Elastic Modulus $E(Kgm/cm^2)$	Poisson's Ratio υ	References
Enamel	8.5×10^5	0.33	(9, 10)
Dentin	2.1×10^5	0.31	(10)
Bone	3.5×10^4	0.33	(11)
PDL (fibrous)	3,500	0.45	(*)
PDL (continuous)	1,750	0.45	(12)

Yoshida and co-workers (2001) [87] determined the elastic properties of the PDL in human subjects based on an FEA model, presenting the forces and stresses required to deflect teeth. From load-displacement relations, Yoshida and co-workers determined the Young's modulus of the PDL as: 0.12MPa under load ranging from 0 to 0.5N, 0.25MPa within the range of 0.5-1.0N, 0.44MPa under load 1.0-1.5N, and between 0.69 and 0.96MPa with 1.5-2.0N [87]. According to Yoshida and co-workers, the values of Young's moduli increased almost exponentially with the increment of load due to a non-linear elasticity of the PDL.

Cattaneo, Dalstra and Melsen (2008) [80] report that the material properties of the PDL in compression and tension are not the same. In compression, the stiffness of the PDL was substantially lower than in tension. These findings are in line with previous research.

Huang and co-workers (2006) [72] evaluated the effects of damping on stress concentrations in an impacted incisor. They suggest that damping material in teeth act as shock absorbers to minimize external impacts. 30 maxillary central incisors were tested in vivo, with a force applied directly on the surface of the incisor in the lingual-labial direction, using an impulse force hammer causing forced vibrations to the tooth. The damping ratios, or fraction of strain energy lost in one full cycle of deformation, of the tested teeth ranged from 0.091 to 0.240 with an average of 0.146 SD 0.037.

Dental Practitioners commonly extract teeth for various reasons with the use of specially designed forceps. In 2003 Ahel and Saracevic [89] designed a manometer based measuring instrument to attach to these dental forceps, and in 2006 Ahel and co-workers [88] measured extraction forces of upper incisor teeth on a control group of 54 patients. The average total pressure measured in extraction of upper incisors in the control group was 1.11 SD 0.28bar. Unfortunately, limited information is available in the paper, and as such there is no way to use these pressure values to suggest extraction forces of the teeth. What was suggested is *"with the increase of tooth surface, the used pressure also increased".*

The literature assessing tooth displacement levels from an injury potential point of view are not as common. The available studies generally suggest that a determining factor of injury outcome of pulp and tooth survival is the stage of root development (i.e. eruption age of the tooth) and the amount of intrusion.

A study performed by Kenny, Barrett and Casas (2003) at the Royal College of Surgeons of England [90] comments on the relationship between depth of intrusion and extent of injury in their study of displacement injuries to permanent teeth. The Royal College of Surgeons of England categorises the amount of intrusion as mild <3mm, moderate 3-6mm and severe >6mm. According to the study, incisors intruded less than 3mm reposition themselves, although obturation of the pulp canal and early pulp necrosis are common. Incisors intruded between 3 and 6mm can be complicated by crown fractures and pulp necrosis. Incisors intruded beyond 6mm are firmly held by compressed bone and do not respond predictably to active repositioning, and require either extraction or immediate reposition followed by root canal treatment [90]. The researchers state *"teeth intruded beyond 6 mm cannot regenerate a functional periodontal ligament and so are prone to root resorption and eventual extraction as well*" [90].

Andreasen, Bakland and Andreasen (2006) [63, 64] also found an association between the depth of intrusion and extent of injury. A study of traumatic intrusion in 216 permanent teeth in 151 patients showed the majority of intruded teeth were displaced 2-8mm. Intrusion of 7mm or more appeared to give a slightly increased chance of healing complications such as pulp necrosis, root resorption and defects in marginal periodontal healing. The authors also looked at the effect of tooth type concluding: "*... lateral incisors showed significantly higher frequency of RR* (root resorption) *than central incisors. ... could partly explain this finding by the more frequent involvement of lateral incisors in multiple intrusions. ... the central incisors showed significantly more frequent MA* (marginal periodontal healing) *than lateral incisors. This finding can possibly be explained by the difference in root anatomy, where the more tapered central incisors possibly release more damage to a periodontium* [sic] *during intrusion compared to the more cylindrically shaped lateral incisors*" [64].

Stages of root development were considered by Andreasen et al. (2006) [63, 64] in their assessment of traumatic intrusion of permanent teeth. They found that stage of root formation at the time of the injury was very strongly related to healing complications such as pulp necrosis and defects in marginal periodontal healing, with immature root formation (i.e. incomplete root formation or completed root formation with wide open apex) having better prognosis than more mature root development.

Hendry, Gilgrass, Chung, MacPherson, Yang and Reuben (2008) [91] performed an in vitro pilot study of an impact test machine to evaluate the bond strength of orthodontic brackets to tooth enamel. The study highlights the importance of the periodontal ligament to the biomechanical performance of the tooth: "*The lack of a simulated periodontal ligament, which is present clinically and acts as a shock absorber, may have contributed to the high failure rate"* [91].

3.3.3 Summary

Information on tooth strength and tooth compliance has been considered in the literature mainly for the purposes of validating the fracture strength of restorative dental substitutes and for determining bone and PDL resorption and remodelling rates for slow rate orthodontic manipulation outcomes. The studies found cover a range of types of study including animal studies, FEA analyses and extracted tooth studies, and to a lesser extent Post Mortem Human Subject (PMHS) and in vivo studies. Very rarely was in vivo experimentation encountered. Studies performed on excised PMHS tooth specimens were associated with numerous problems including; poor condition due to age; effect of freezing and embalming on the mechanical properties of the specimens; fixation issues shown by the need for acrylic embedment in Prabhakar, Jurthukoti and Kayalvizki's study [65]; and force application issues shown by the need for grooving of specimens in Rasmussen, Patchin, Scott and Heuer's study [77]. The most relevant studies involving human dentition indicate a force tolerance limit of 120-220N for maxillary incisors, and a deflection tolerance limit of 2-6mm for permanent injury and greater than 6mm for tooth avulsion.

3.4 Biomechanical Effects of Embalming on the Dentition

PMHS can be either in fresh, frozen or embalmed condition. Each method of preservation has its own effect on the mechanical properties of bone and ligaments, however as the specimens to be used in this study were embalmed we will only consider those here.

Since the late sixties, limited dynamic testing has been performed on embalmed cadavers due to the commonly accepted lack of biofidelity required for impact testing due to the tissue rigidity and joint inflexibility. It is commonly assumed, however, that embalming results in softer bones and laxer but stiffer ligaments. As explained by Crandall, Pilkey and Sturgill, tissue preservation is accomplished through a chemical "fixation" or coagulation of the proteins which is not normally present in the living tissue [105].

A summary of some prominent studies of the biomechanical effects of embalming on human bone and soft tissues is presented below. Although many of the effects of embalming on ligaments and bone are discussed in the literature, and only a selection are presented here, no study has looked at the effects of embalming on the PDL, roots, pulp, gums, dentin or enamel. It is assumed that the effects on these dental structures will be consistent with the effects seen in other parts of the body.

Summary of selected studies of the biomechanical effects of embalming on human bone:

- Embalming with formalin increased the bending strength of human long bones, Carothers, Smith and Calabrasi (1949) [106].
- A loss of compressive strength of approximately 13% occurred in embalmed human compact bone specimens, Carothers, Smith and Calabrasi (1951) [107].
- Embalming with formalin increased the modulus of elasticity in human femurs, Sedlin (1965) [108].
- Uniform increases of approximately 10% in the mechanical properties when comparing all varieties of embalmed and fresh bone, Yamada and Evans (1970) [109].
- Embalming with formalin increased the tensile and hardness properties of human tibial samples, Evans (1973) [110].
- Embalming with formalin decreased the ultimate compressive strength of human tibial samples, Evans (1973) [110].
- Formalin fixation did not affect the elastic modulus, the ultimate stress and the hardness of human cortical bone on a short-term perspective, whereas long-term preservation (8 weeks) did have a significant effect on the elastic properties, Ohman (2008) [111].

Summary of selected studies of the biomechanical effects of embalming on human soft tissues:

- Formalin treated connective tissue showed decreased tensile strength of up to 65%, and increased stiffness due to cross linking of collagen when compared with fresh fibres, Highberger (1947) [112].

3.5 Conclusions

A review of the literature has allowed the necessary background information on the dental anatomy, tooth injury mechanisms, dental injuries in sport and mouthguards to be summarised, and enables the scope of the project to be outlined.

The structure of the teeth and the relative properties of each component of the dentition help us to understand the importance of assessing a tooth along with its supporting structures, such as the gingivae (gums), the root and the PDL, rather than as an excised stand-alone tooth. It highlights the difference between each type of tooth and root system and as such the importance of considering each tooth type separately in terms of their biomechanical properties and injury tolerance limits.

The most commonly seen injuries, including chipped teeth, tooth fractures, tooth dislocations and or displacements and trauma to the structures supporting the tooth in the alveolar socket re-iterate the need to assess the tooth system as a whole, and help to define what can be visually assessed when considering injury tolerance levels. The limited information available regarding the mechanisms of these injuries highlights again the involvement of the supporting structures in the outcome of tooth injury, and the necessity to design a method of assessing not only the visual damage to the exposed section of the tooth, but also the hidden support structures housed in the alveolar socket. The limited information on injury mechanisms to the teeth also highlights the ability of this study to make an original contribution to the field.

As the most commonly injured teeth are the maxillary central and lateral incisors, this allows the focus of research to be concentrated on the single root anterior teeth, simplifying the testing and research involved.

Through the extensive work of researchers in defining head impacts during sporting activities to assess injury outcome on the TMJ and brain, it is possible to define the scope of sporting impacts which are associated with mouthguard use. The literature indicates sporting impacts to the head mostly occur to the face (including the mandible), and are most injurious when orientated directly frontal, or in an uppercut motion.

The research also shows there is a significant difference in injury type when impacts occur with large, slow, soft objects, such as soccer balls and body regions, and smaller, faster, harder objects such as pucks, goal posts, hockey balls and baseballs. Impacts occur at a range of speeds, anywhere from 1.7m/s to 18m/s, and are associated with head acceleration levels ranging from 32g to 210g. Injurious impacts are associated with either impacting speeds of 2-20m/s, or resulting head acceleration levels of above 80g.

Despite the amount of information known about the teeth generally and sporting impacts to the head and maxillofacial region, the severity of TMJ and MTBI injuries has limited the amount of research being undertaken on the dentition. As such, the information available about the strength and compliance of the teeth is narrowed to dental repair and orthodontic manipulation technologies.

The studies found have highlighted the near impossibility of testing living tooth specimens, and the difficulty in testing intact teeth and their natural support systems. The majority of the biomechanical information available is either for dentin or enamel, with suggestions of force levels of 0.16KN to 2.2KN (160N to 2200N) seen in mastication of food items implicated in tooth fracture, and force levels of 12kg to 21kg (117.7N to 206N) reported for fracture of the maxilla incisors. Displacement of the tooth of 3-7mm has been reported to be associated with permanent injurious outcomes including pulp necrosis, root resorption, defects in marginal PDL healing, and tooth death, leading to tooth extraction if it didn’t avulse in the first place.

The study of tooth displacement following the application of orthodontic loading regimes has shown the importance of several and complex parameters such as material properties of periodontal tissues, shape and length of tooth, width of the PDL, and the marginal bone level on the biomechanical performance of the tooth, again highlighting the necessity to assess the tooth and root structure as a whole, which is an area of research lacking in the field of mouthguard effectiveness studies.

Although mouthguards are promoted for use and are commonly worn in sporting events where there is a serious risk of a blow to the mouth or jaw area, the stated 60-80% reduction in dental injuries is not sufficiently supported, nor properly defined. By understanding better the tooth responses to impacts and the injury mechanisms the properties of mouthguards can be assessed to improve the injury reducing potential of these devices.

4. Existing Test Methodologies

The literature review of tooth injuries undertaken in Chapter 3 of this study has revealed the gap in knowledge regarding the dentition's biomechanical response as a result of impact. It has also highlighted the need for a more meaningful and insightful test methodology for testing the effectiveness of mouthguards in preventing or limiting injury to the dentition.

On the quest to design a method for testing the amount of deformation and level of force required to produce permanent injury to the dentition, a review of existing mouthguard and or tooth test methodologies and existing test surrogates was necessary. As outlined earlier, the Australian and International Standards for mouthguard testing are material based tests and thus do not encompass the full problem being addressed here.

4.1 Existing Methodologies for Assessing Biomechanical Properties of Teeth

It was apparently in 1980 that the first research on tooth extraction measurements in patients was undertaken, by Ojala and Lehtinen [88, 92-95], which under review from subsequent studies was flawed as they were more likely assessing the capability of the operator to preform the extractions rather than the properties of the actual teeth [88].

Ahel and co-workers [89] attempted to measure in vivo tooth extraction forces using a measuring instrument patented by Ahel and Saracevic in 2003 [89]. Ahel and co-workers took the specially designed existing forceps dental practitioners commonly use to extract teeth, and fitted them with monometers (**Error! Reference source not found.**) [89].

Ahel and co-worker's study is typical of the majority of reviewed studies investigating the injury tolerance levels of the dentition, which record measurements through instrumented impactors. Rarely were studies performed where measurements were taken from instrumented teeth. Those that were, were performed on excised individual tooth specimens. The most commonly used methods of measurements were strain gauges and force transducers. Displacement measurement techniques of the teeth were either performed by displacement measurements generated by the impactor, or were not explained. However, there are many known methods used to measure the relative motion of two bones including goniometers, video cameras, electromagnetic sensors, optical devices, and fluoroscopy to name a few.

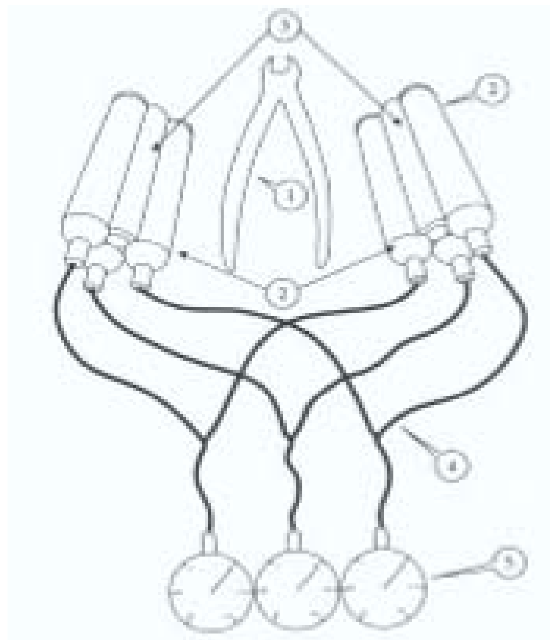

Figure 14 Instrument used to measure extraction forces in Ahel et al. (2006) [88]1 – forceps, 2- three part air bags silicone rubber, 3- cylindric transitory holes, 4- connecting tubes, 5-manometers.

One method of measuring small motions (i.e. 2-6mm) in multiple directions which has not been explored for recording tooth deflection is the Optotrak Marker system. According to Maletsky, Sun and Morton (2007) [96] the accuracy of an Optotrak active marker optical system is greater than specified by the manufacturer. The stated accuracy of the system, as reported by the manufacturer for each individual sensor is 0.1mm for the viewing plane of the cameras, and 0.15mm directed towards the cameras. Maletsky and co workers found that although increasing the camera distance increased the measured noise, in the range investigated 1.75-4.0m the noise was around 0.041 and 0.03 mm. The researchers speculate this level of accuracy is acceptable for most biological experiments and generally better than the noise with other systems [97, 98]. This level of measurement accuracy is adequate for the 2-6mm deformation hypothesised for tooth injury to occur (based on the literature presented in Chapter 3 above) and allows for the sensors to be attached directly to the tooth via a rigid body marker tool, without compromising the intact dentition specimen.

4.2 Existing Test Surrogates

Unfortunately, there is no commercial surrogate headform currently available which has been validated using chin impact response data, nor is there a commercially available surrogate headform with an articulating jaw that can be used in the evaluation of mouthguards. Various surrogate biofidelic headforms, however, have been developed to study head impact responses in automotive applications and for assessing helmet performance.

The most common include the modified Hybrid III headforms, and headforms developed by the National Operating Committee on Standard for Athletic Equipment NOCSAE. Craig, Viano and Bir (2009) [26] performed a study which compared the biofidelity of a selection of surrogate headforms with cadaver studies, based on the impact response performance for impacts to the jaw. The responses of 8 different Hybrid III and NOCSAE based headforms to mid-sagittal loading at the chin were compared to PMHS data using average peak response and cumulative variance data. Their findings state "*the surrogate that performed best overall was the Hybrid III 50th with an articulating jaw and shore 70A hardness condylar bushings. Using the biofidelity ranking system of Rhule et al. (2002)* [99]*, the 70A surrogate demonstrated "good" biofidelity in all force and displacement based measures*" [26]. None of these test surrogates, however, had dentition or allowed for the placement of a mouthguard in the maxillofacial region to assess the influence such a device has on force transference.

Some individual studies have constructed one off test surrogates which allow for assessment of dental impacts, however generally speaking these surrogates are not biofidelic. For example, a study in 2001 performed by Warnet and Greasley [100] simulated impacts to the jaw in an attempt to determine the required force to produce tooth fractures. The study used a spring mounted simulated jaw with ceramic teeth inserted into a hard rubber arch reinforced with a composite jawbone.

Perhaps the most relevant and appropriate existing test methodology is that designed and developed by Biokinetics and associates in Ottawa, Canada. Stemming from investigations on concussion and head injury in sports for the National Football League (NFL), in 2010 Biokinetics constructed a specialised headform capable of investigating mild traumatic brain injury MTBI outcomes from jaw impacts and the influence of wearing a mouthguard [26-28].

Their test methodology uses a Hybrid III 50^{th}% male headform with an articulating jaw, which is instrumented with force transducers to measure head accelerations and force transmission through the upper dentition and the left and right TMJ. The altered, instrumented headform is shown in Figure 15 and Figure 16. The biofidelity of the headform for TMJ responses has been verified through drop impacts to the chin of cadaver specimens performed by Matthew Craig [26-28]. This work is being funded by the NFL and is still in progress.

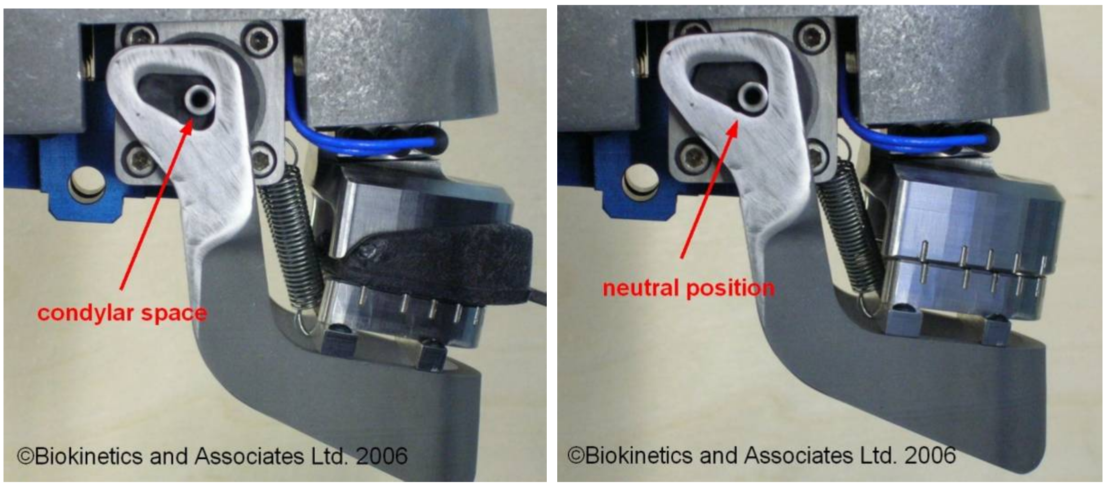

Figure 15 Headform with a mouthguard in place and the TMJ in the neutral position, from Biokinetics.

Figure 16 The instrumentation fitted to the jaw and TMJ of the headform, from Biokinetics.

The Biokinetics headform is to be used for assessing the ability of different mouthguard designs to affect the head injury potential from impacts through a football helmet. Research will also be conducted into the effect chin straps and facemasks have on head accelerations.

Although the headform does not allow for assessment of individual tooth responses to impacts, it provides the basis for a test methodology for measuring the forces acting on the maxilla, and transmitted through to the TMJ, allowing for an assessment of mouthguard performance in a formed capacity as opposed to a materials test. If the injury tolerance levels of the dentition can be defined and properly understood, it may be possible for this information to be incorporated into the headform essentially allowing the possibility for the test methodology to form a basis for a new Standard for mouthguard performance in the future to replace or enhance the existing Standards.

4.3 Biokinetics Test Methodology

The test methodology used in conjunction with the Biokinetics headform is based on the methodology used in the cadaver testing performed by Matthew Craig [26-28], which stemmed from the works of Pellman, Viano, Withnall, Schewchenko, Bir and Halstead (2006) [101] and Waliko (2004) [102]. It models impact loading of the chin by dropping a 5.2kg drop mass from various heights onto the chin point of a mounted cadaveric specimen. In the cadaver tests, each head was disarticulated above the first cervical vertebra and secured in a fixture with polyester resin. The specimen's jaw was positioned in normal occlusion with maximum intercuspation.

The drop mass impact technique used by Biokinetics and Associates is shown in Figure 17 [28]. The test stand has an aluminium frame supporting a tube for guiding a drop mass and an aluminium reaction surface. Steel plates and a centre support are used to further reinforce the stand. The drop mass incorporates a 20.3cm^2 circular impact surface and the foam padding on the drop mass is 18mm thick, closed cell, 3.8pcf polyethylene [28]. The apparatus is capable of using different drop masses and varying drop heights to achieve the desired impact energy.

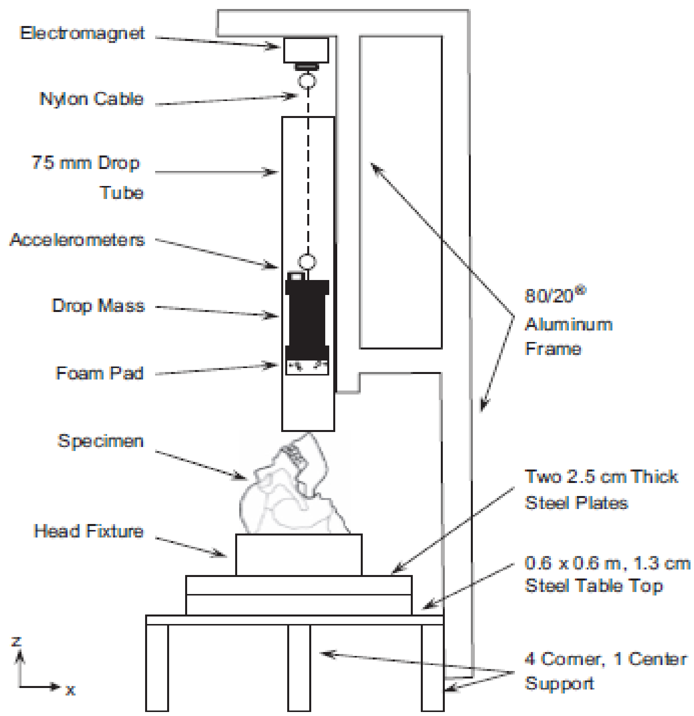

Figure 17 Drop mass impact test technique of Biokinetics and Associates [28].

Craig et al. [28] used radio-opaque markers adhered to the surface of the bone, and a high-speed bi-planar X ray system (Henry Ford Hospital, Detroit, Michigan) to record marker displacement. Drop mass acceleration was measured in the x-, y- and z-directions with EndevcoTM 7264C-2000 single-axis translational accelerometers and collected using TDASPROTM (DTS, Inc., Seal Beach, California) at 1000Hz. Drop mass force was calculated as the product of the drop mass weight and z-direction acceleration. Acceleration data were filtered using a 1650-Hz Butterworth filter (SAECFC1000).

4.4 Mouthguard Testing using the Biokinetics headform

As a side investigation as part of this Masters study, a test series was commissioned through Biokinetics using the Biokinetics headform to test a selection of five mouthguards manufactured by Myofunctional Research Co. (MRC) (Helensvale, Australia), funded by Human Impact Engineering (HIE) (Sydney, Australia) and MRC. The tests were performed as per the testing outline above and in Craig's published work [28], and compared to a no mouthguard control condition. For this test series, three impact loading conditions were considered (Figure 18) including an impact to the chin, an uppercut and a direct frontal impact. Due to time and cost restrictions, each load condition was only tested three times for each mouthguard model. The averaged forces recorded by the upper force transducer (representing the upper dentition) in the direction of impact for these tests are presented in Figure 19 and Figure 20 for the uppercut and direct frontal impacts respectively.

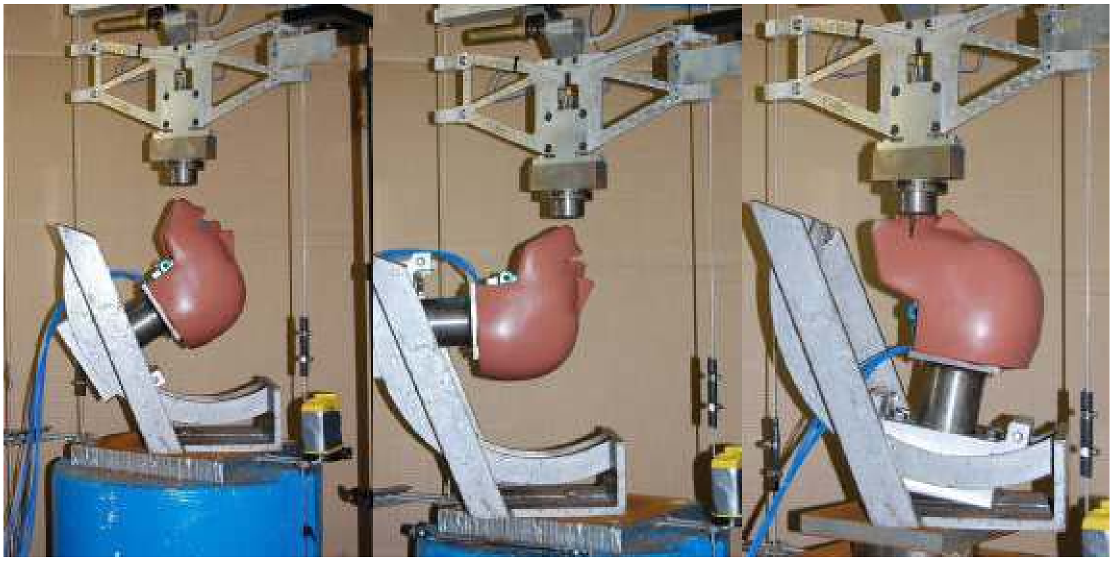

Figure 18 The three impact loading conditions used in the MRC test series. Left – an impact to the point of the chin (condition 1); Centre - an uppercut impact (condition 2) and; Right - a direct frontal impact (condition 3).

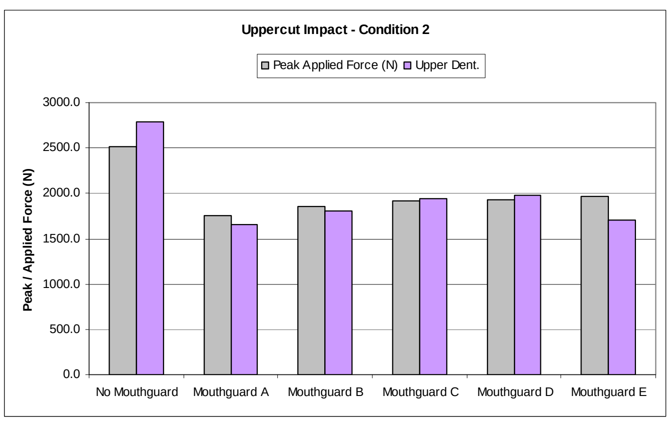

Figure 19 Comparison of applied force and force experienced by the upper dentition under uppercut impacts (condition 2).

As expected, the uppercut impact tests showed that the presence of a mouthguard reduced the peak applied force and upper dentition force under an impact in comparison to the no mouthguard control test. The testing also indicated a larger scale test series could consider the effect of phasing on the upper dentition load which sees the upper and lower dentition being pressed against each other after the initial impact, and the effect of the thickness of the mouthguard model on the force transmitted.

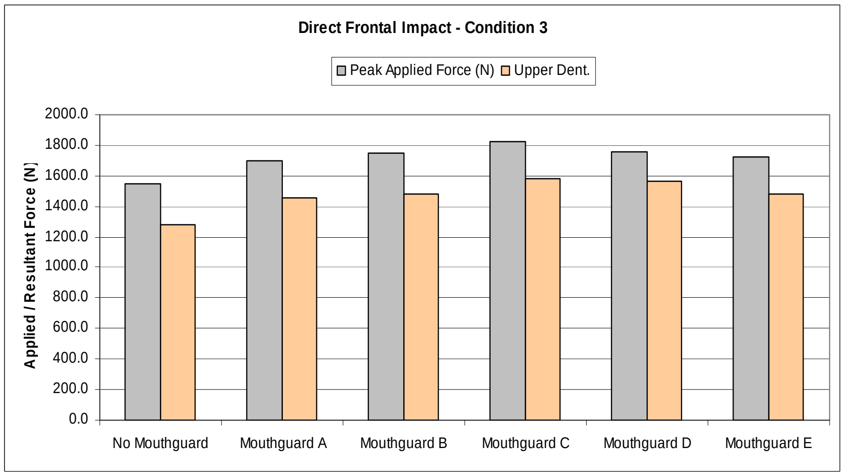

Figure 20 Comparison of applied force and force experienced by the upper dentition under direct frontal impacts (condition 3).

The direct frontal impacts however depicted a different picture. In all tests it appeared from the data that the upper dentition force was less than the peak applied force, however the difference in the applied force compared to the upper dentition force was less in the mouthguard model tests than the control no mouthguard test. All mouthguard models recorded greater applied force and upper dentition force levels overall than the no mouthguard control test.

From this testing, it can be seen that mouthguards have a greater effect on reducing the force transmitted to the upper dentition during upper cut type impacts in comparison to direct frontal impacts, however the presence of a mouthguard will always ensure the force delivered to the dentition is less than the peak applied force. The materials test performed on a mouthguard in the Australian Standard does not take into consideration the forming effects on the mouthguard, or the fit of the mouthguard in the mouth to allow for a proper coupling between the teeth and the mouthguard. Although Biokinetic's test methodology does allow for the forming and placement of a mouthguard, due to the hard, flat, uniform surface of the simulated metal dentition, it is possible that the mouthguard may not have stayed in place during the impact as it would have if properly fitted in an anatomically accurate human mouth. More investigations as to why the forces experienced by the dentition are increased with the presence of a mouthguard compared to no mouthguard under a direct fontal impact are needed.

Although this existing test methodology provides a way to assess whether mouthguards may reduce the applied force transmitted to the dentition, there is no way of telling if the applied force is reduced by enough to substantially make a difference to the injury outcome.

4.5 Conclusions

Through a review of the lack of existing test methodologies, and a test series performed on the Biokinetics Headform, it can be said that the purpose of this Master's study is compelling. Existing measurement techniques and test surrogates have not been designed or constructed with the intact, naturally supported dentition in mind.

By developing a method for testing the amount of deformation and level of force required to produce permanent injury to the dentition, new information will be available that will provide an original and crucial contribution to the field. It is anticipated that this test methodology can then be used to define the injury tolerance levels of the intact, in vivo dentition, under impact loading which could form the basis for the development of a biofidelic test surrogate to assess, and in turn improve, the protection offered by mouthguards.

5. Developing a test method

Developing a method for testing the amount of deformation and level of force required to produce permanent injury to the dentition would allow for a significant, innovative contribution to the fields of biomechanics and dentistry, and have wider value for other applications. Hence it is important to develop as accurate and meaningful a test method as possible.

Having said this, there are certain limitations, assumptions and considerations that first had to be incorporated into the design of the test methodology. These are discussed below.

5.1 Limitations, Assumptions and Considerations

Before reproducing dynamic sporting impacts at the high speeds demonstrated in the literature it was important, initially, to develop a quasi-static test to ensure test protocols and instrumentation were adequate to acquire the necessary data. A limitation of performing quasi static loading was that the rate dependant response of the tissues may be different to that under high impact dynamic loading. As the literature highlighted the difference in injury outcome as a result of the speed, mass and size of the impacting object it was deemed necessary to perform future testing with dynamic loading. The test methodology therefore must allow for both quasi static loading and full impact loading. Re-evaluation of the testing impacts was to be undertaken as the study progressed.

As it has been deemed that the intact condition of the tooth and supporting structures was crucial to the assessment of injury tolerance of the dentition, this study aimed to use the most appropriate intact specimens. Research was undertaken into the use of bovine or porcine dental segments as substitute for human specimens, however, due to the differing chemical, structural, anatomical and radiographic characteristics of these animal teeth, they were deemed inappropriate for this study [32, 103, 104]. As the use of human specimens was necessary but loading living subjects' teeth was inappropriate, Post Mortem Human Subjects (PMHS) were decided upon. To simplify the design of a test methodology and apparatus capable of housing whole heads or bodies, it was decided to use just the maxilla, which was excised prior to testing. Whole maxillae were required to ensure the dentition and supporting structures remained intact.

Because the aim of this study was to find a way to determine the injury tolerance of the dentition, a way of assessing injury to the teeth and or supporting structures as a result of the delivered loads was central to the study. As the literature suggested that injury could occur past what the naked eye can see, it was decided that the specimens would be micro CT scanned (Scanco μCT40, Scanco Medical, Switzerland) prior to testing to define a base line of the condition of both the dentition and supporting structures. A further micro CT scan was then to be conducted post testing in order to define any non-visible injury sustained. Consideration was required in preparing the specimens to ensure they fitted into the micro CT canister. Micro CT scanning had not been used in this manner before, so this in itself was a trial of the capabilities of the micro CT scanner to obtain such information.

5.2 Design of a Test Apparatus

As seen with previous studies, there are limitations as to how the biomechanical responses of the teeth can be measured. To simplify this, only the two main characteristics, deformation and force, were assessed in this study.

The design of a test apparatus required allowing for the mounting of the specimen, and a device for applying a direct load to the surface of an individual tooth. In the most basic of design starting points, based on ideas drawn on from existing test methodologies and reviewed literature, the original concept design idea behind the testing apparatus is shown in Figure 21.

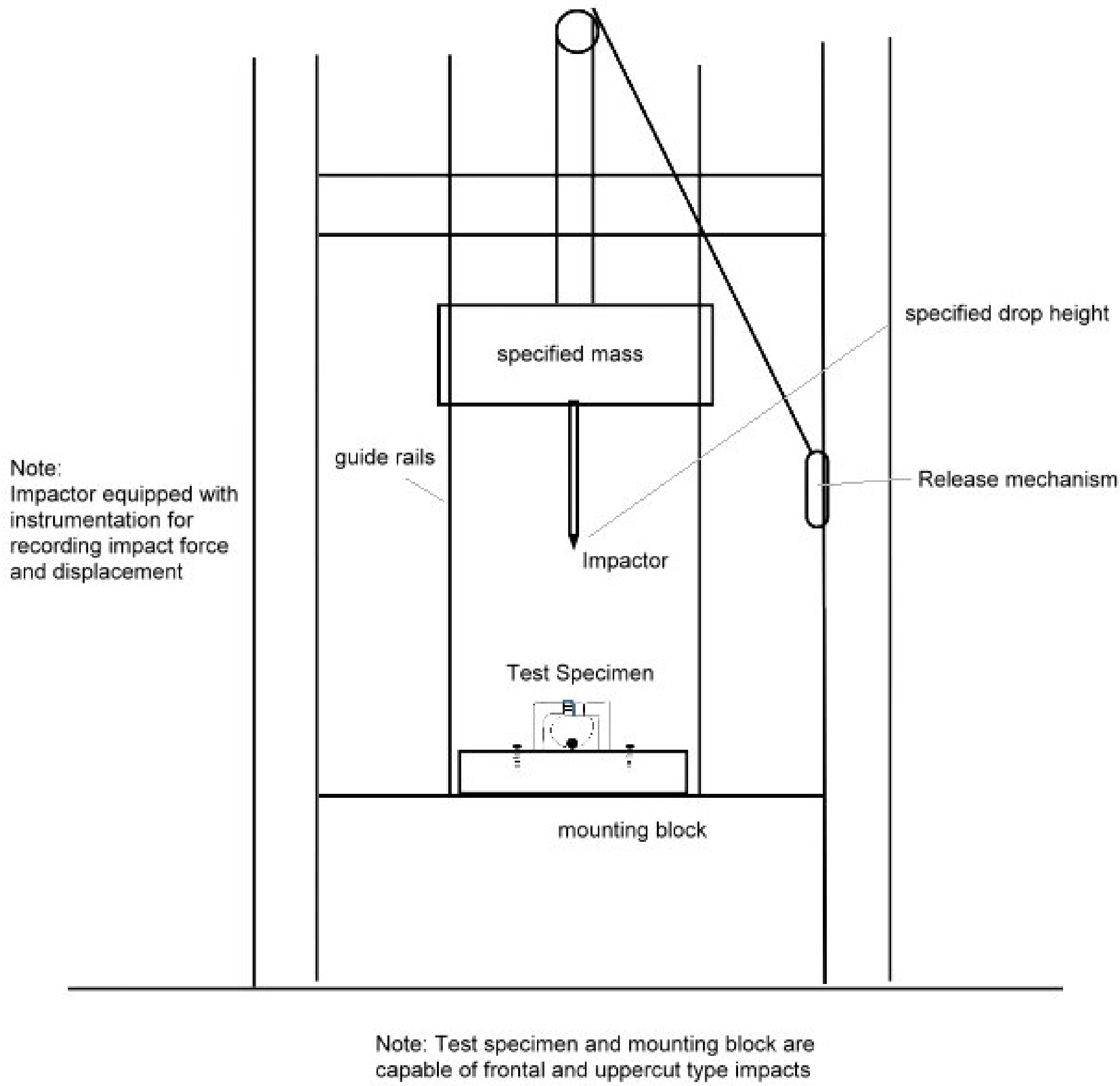

Figure 21 Original concept design idea for test apparatus.

The design of the impactor and drop rig was superseded by the choice of using an Instron materials testing machine (Bluehill 30kN Instron machine; Instron Ltd., High Wycombe, UK). This choice was made as it eliminated the need to manufacture a new test rig as the Instron machine was already available for use, and to simplify the process of designing and setting up instrumentation for recording loading and force measurements, as the Instron machine was already equipped with the necessary data acquisition technologies to perform this. It was assumed, based on the reviewed literature, that a 5kN load cell was sufficient in the Instron machine for this testing.

To complement the loading and force measurements acquired by the Instron machine, a method for measuring small 3D displacements of loaded teeth was needed. From the previous literature review of existing measurement technologies, the Optotrak motion analysis system (Northern Digital Inc. (NDI) scanner and data acquisition box; NDI, Waterloo, Ontario, Canada) was an option worth exploring as it was a system available for use through QUT. As the Optotrak marker system had not been used in this manner before, this test series was in itself a trial of the capabilities of the system to measure such small movements.

5.3 Design of a housing to mount the specimen

A housing to mount the specimen for use in the test methodology took into consideration the following functional properties:

- Ability to sufficiently clamp the test specimen in place to restrict the movement of the specimen in the test rig, and restrict the amount of tension and or compression force applied to the specimen from the test rig.
- Ability to clamp and release the specimen without causing any further damage to the specimen.
- Ability for the test rig to house specimens of different sizes.
- Ability to mount the apparatus in the Instron machine.
- Ability to orientate the impactor with the tooth frontal surface and bottom edge to simulate direct frontal impacts and uppercut type impacts.
- Ability to attach Optotrak markers to the individual tooth to track deformation of the tooth.
- Ability to attach Optotrak markers to the maxilla/mandible bone of the specimen to allow for measurement of the tooth with respect to the jaw.

The final design of the specimen housing apparatus is shown in Figure 22. This apparatus was manufactured by rapid prototyping (Figure 23). Initial tests were conducted on a wooden block simulating the maxilla and then a specimen maxilla was produced by rapid prototyping from the CT scan of a PMHS.

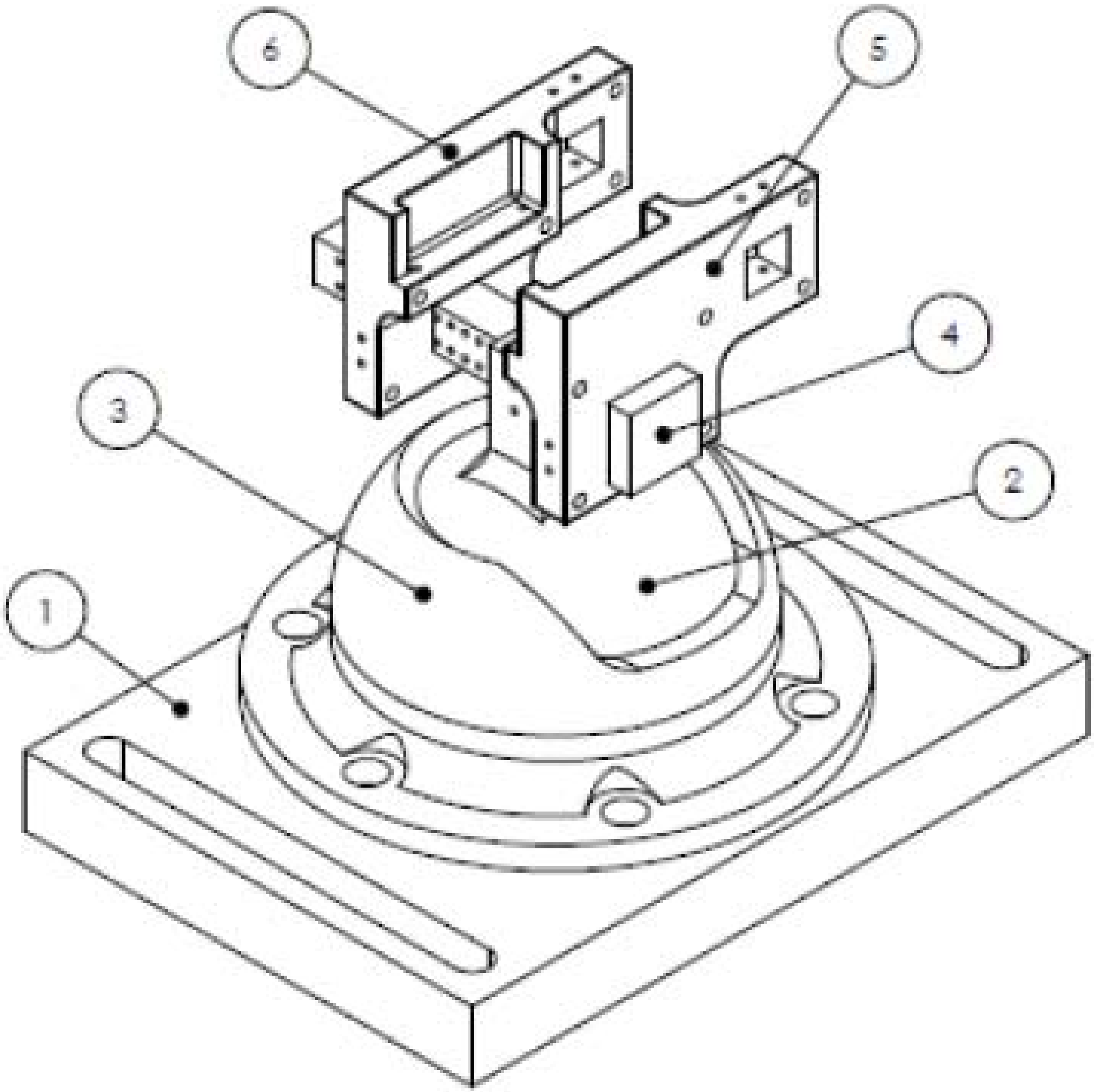

Figure 22 Design of Test rig for housing cadaveric tooth specimens, 1. – *Base plate* for attachment to the Instron machine, 2. – free moving *Ball* to allow for presentation of the tooth's front surface to the Impactor, with stem for attachment to the *Peg* (4), 3. – *Ball Sleeve* to clamp down on the *Ball* (2) and hold it in place once aligned, 4. – *Peg*, to allow for adjusting the size of the *Clamps (5)* to fit different sized specimens, 5. – *Clamps* to hold the specimen in place. The clamps slide along the *Peg* (4), and 6. – Foam lined notches in the clamps to protect the specimen and allow for a better interface between the specimen material and the rapid prototyped material.

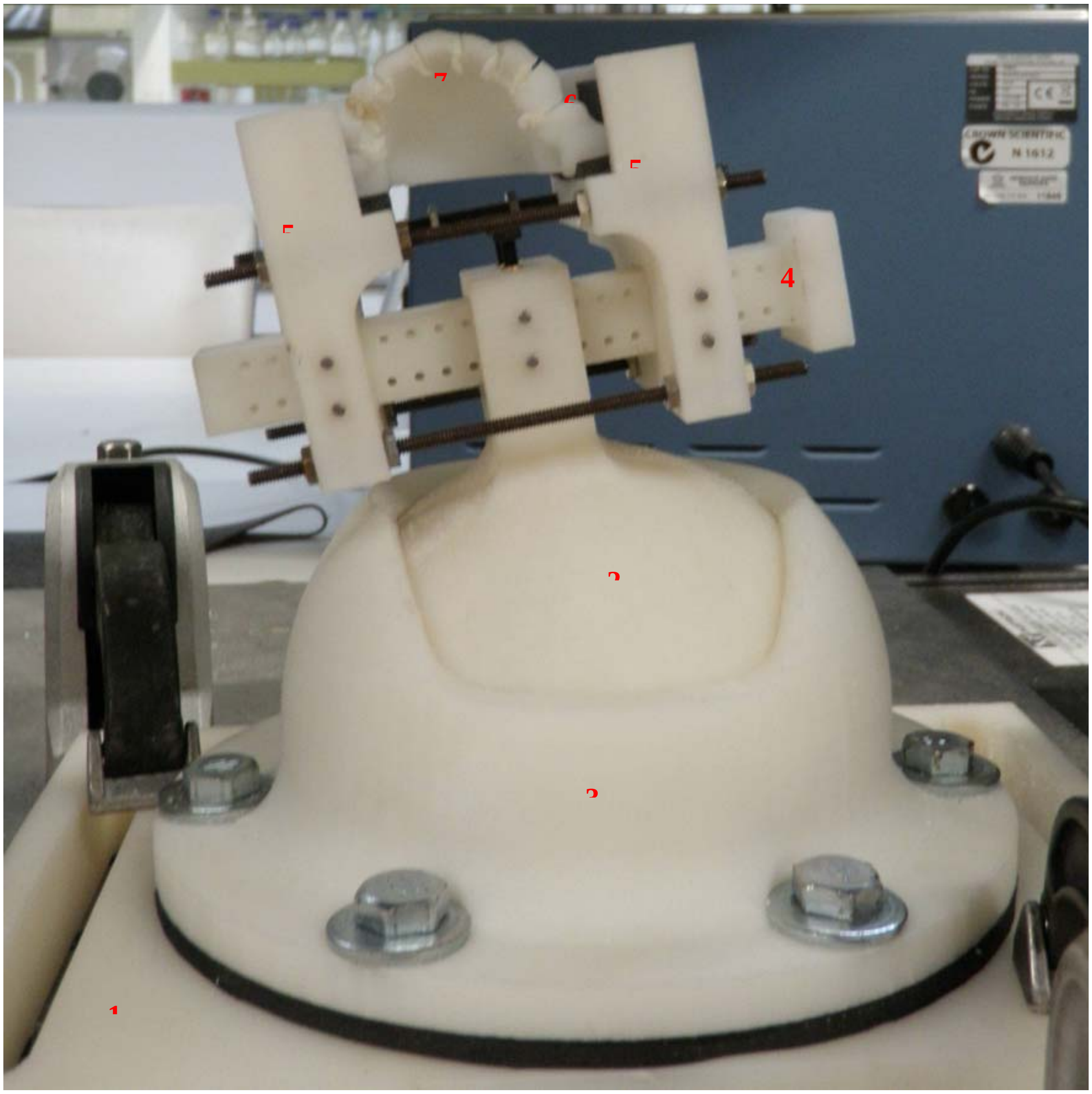

Figure 23 Test rig manufactured for the housing of cadaveric tooth specimens. 1. – *Base plate* for attachment to the Instron machine, 2. – free moving *Ball* to allow for presentation of the tooth's front surface to the Impactor, with stem for attachment to the *Peg* (4), 3. – *Ball Sleeve* to clamp down on the *Ball* (2) and hold it in place once aligned, 4. – *Peg*, to allow for adjusting the size of the *Clamps (5)* to fit different sized specimens, 5. – *Clamps* to hold the specimen in place. The clamps slide along the *Peg* (4), 6. – Foam lined notches in the clamps to protect the specimen and allow for a better interface between the specimen material and the rapid prototyped material, and 7. – Rapid Prototyped *specimen.*

The inside surfaces of the holder the specimen was to sit in were lined with black foam for better moulding to the specimen to secure it in place. The specimen was placed in the housing and the clamps positioned with pins through the alignment holes to hold the specimen in place then tightened above and below the peg through the nuts and screw bars (Figure 24). The test rig was clamped to the base plate of the Instron machine. The ball and socket was clamped together after achieving the desired alignment of the specimen by 6 self-locking bolts, with a thin layer of black foam between the base plate and the socket.

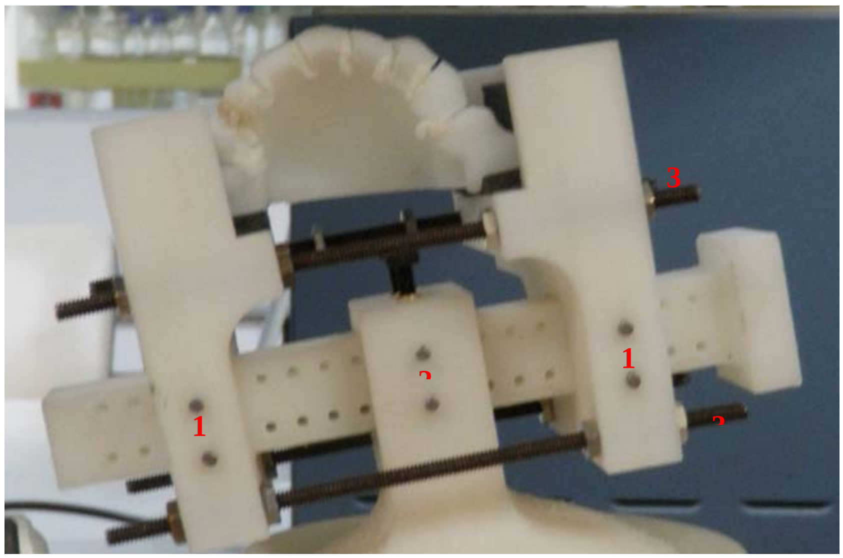

Figure 24 Close up of the mounting of the specimen in the housing, showing 1. – pins in alignment holes securing clamps to peg, 2. – pins in alignment holes securing peg to ball, and, 3. – Tightening of specimen in housing with nut and screw bars.

5.4 Test procedure

Modifications were made to the under surface of the Instron attachment to allow for the load to be applied directly to an individual tooth. These modifications consisted of the placement of a t-shaped metal nail with a flat head super glued to the bottom surface of the Instron attachment. This was termed the 'impactor'. It was necessary for the impactor to be securely fastened yet not involve permanent changes to the load cell, thus superglue was used as it is known that the super glue bond can be dissolved when needed. The impactor fixed to the Instron attachment can be seen in Figure 25.

Figure 25 The attachment of a tack shaped metal nail with a flat head to the Instron attachment to allow for loading a single tooth.

Based on the available literature, initial tests began at loads of 50N with responses considered before increasing the applied load in increments of 50N until permanent deformation of the specimen was seen.

Initially quasi-static loading was performed at a rate of 1mm/min. In later tests, in an attempt to reduce the slippage of the impactor on the tooth's surface, the rate was increased to 3mm/min. Details of when this occurred are included in the results and discussion below.

5.4.1 Pilot Study

The proposed test method and apparatus were used in a pilot study to assess how well the specimen was held by the rig and to establish protocols for testing and for placement of the Optotrak markers for measuring deformation of the specimens. This pilot study used a wooden block in the test rig to ensure the specimen could be clamped as desired and allow for orientation of the specimen in six degrees of freedom of motion (three rotations and three translations), to allow individual surfaces of a tooth to be presented to the test machine. Three tests were performed on the wooden block up to 50N. The Instron machine load vs. deflection graphs for Wood Test 2 is shown in Figure 26 for reference. It was deemed that this was acceptable for a base line pilot study, and showed the capabilities of the test apparatus and specimen housing to withstand the desired loading.

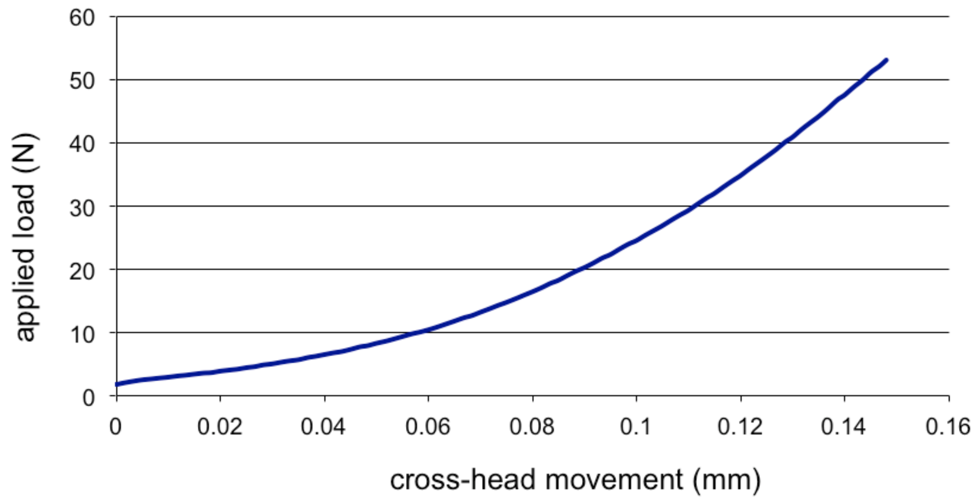

Figure 26 Instron applied load vs cross-head movement results for Wood Test 2.

The pilot study also demonstrated the ability of the Optotrak system to be attached to the test rig and specimen housing. Groups of four Optotrak markers were combined on rapid prototyped mountings to attach to the Instron cross-head, the test rig base plate, and the peg of the specimen housing. Additional Optotrak marker groups were prepared onto rapid prototyped (RP) mountings for attachment to the tooth and maxilla specimens, however, these were not all trialled in the pilot wood tests. Although the Optotrak system was set up to assess linear displacements and rotations, for the purposes of this study the results were limited to linear displacements only. The maxilla 'bone' marker was nailed into the block of wood to monitor the motion of the specimen in the wood tests.

The motion of the Instron cross-head, the test rig base, the test housing peg and the block of wood were successfully traced by the Optotrak markers during the pilot tests. As expected, linear movement was seen of the Instron cross-head in the direction of applied force, and no motion was seen in the test rig or peg marker traces indicating negligible movement in the specimen housing or test system under these loads. The traces for the markers attached to the wooden block (Figure 27), suggest the Optotrak system detected compression of the wooden block due to the 50N load applied, and therefore was capable of detecting small movements necessary to this study.

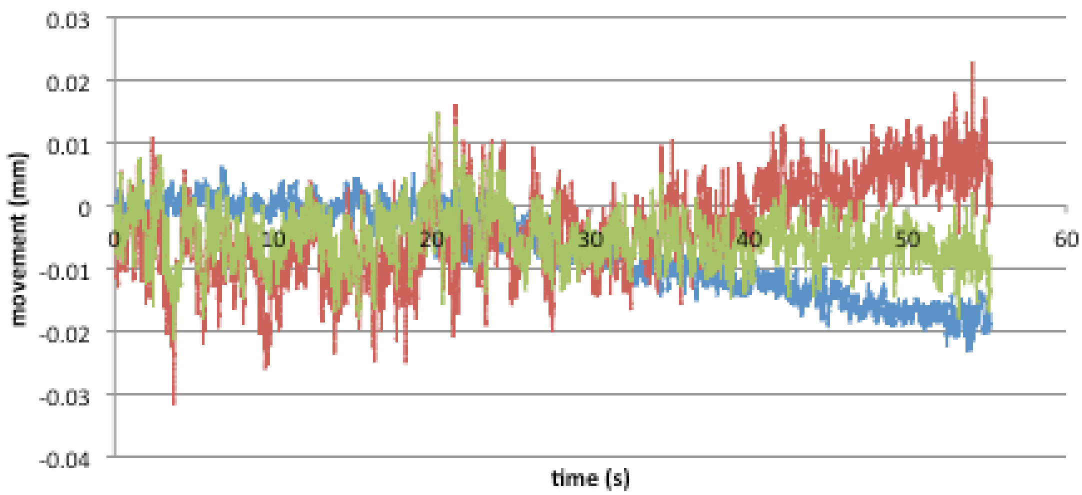

Figure 27 Optotrak motion traces (zeroed) for the markers attached to the wooden block specimen during pilot testing, showing vertical motion (blue), horizontal motion (green) and fore/aft motion (red).

Based on the combination of Instron and Optotrak results, the pilot study was deemed successful in proving the test methodology, and testing proceeded to Rapid Prototype specimen testing.

6. Testing

6.1 Rapid Prototype Testing

Due to the unique nature of this testing, a Rapid Prototype (RP) model of a cadaver specimen was made for use in a series of preliminary tests, performed after the pilot study but before using cadaver specimens. Ethics approval was obtained from the QUT Human Research Ethics Committee to conduct tests on human specimens (QUT Ethics approval number 1000000572). Post Mortem Human Subjects (PMHS) at the Medical Engineering Research Facility (MERF) at QUT were inspected and the most appropriate in terms of dental appearance, number of natural teeth in the best condition and requiring the least amount of preparation in terms of removing fillings and bridges etc. was selected and CT scanned. Scanned images are shown in Figure 28. Using the CT scan a rapid prototyped skull, mandible and maxilla were printed. A photograph of the printed RP specimen is shown in Figure 29.

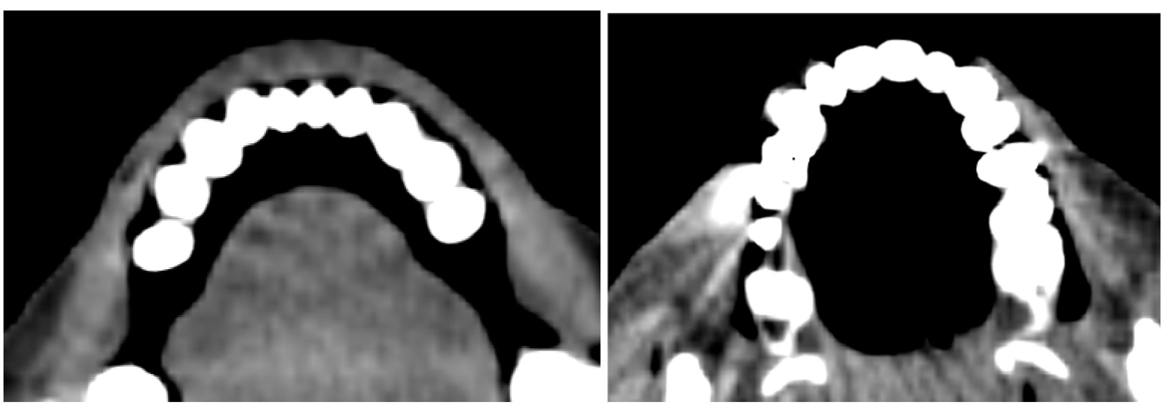

Figure 28 CT scan image of PMHS mandible (left) and maxilla (right) selected for the basis of a rapid prototyped model.

Figure 29 Rapid prototyped skull including mandible and maxilla from a CT scan of the cadaveric specimen.

The maxilla was cut from the RP face, and trimmed to size in the same manner that the actual specimen would need to be to allow for placement into the micro CT canister. This also served as a trial to ensure enough of the maxilla bone and the dentition's surroundings would remain around the front teeth to ensure the dentition's supporting structures would still be intact for the PMHS testing. The final trimmed maxilla and upper dentition RP model used in the preliminary tests is shown in Figure 30. The resolution of the scan and printing did not permit individual teeth to be printed and so small cuts were made through the RP maxilla to separate individual tooth structures.

Figure 30 Rapid prototyped maxilla from the CT scan of a cadaveric specimen trimmed to the desired size showing the cuts to separate the individual teeth.

The specimen was then placed in the housing, and the housing secured to the test rig. The test protocol followed and subsequently adapted and used for the PMHS testing is provided in Appendix A. The test matrix of the RP tests performed is shown in Table 8. The RP tests were performed by first preloading the RP tooth to 5N to ensure there was contact between the impactor and the specimen in the desired place. For all tests, visual alignment of the impactor was undertaken to position the tip of the nail in the approximate centre of the tooth's frontal surface. Visual alignment was also used to position the tooth's frontal surface perpendicular to the impactor. Quasi static loading was delivered at a rate of 1mm/min via the Instron machine.

Table 8 Summary of Rapid Prototype Tests.

Test Number	Impacted tooth	Peak Applied Force
RP #1	Front left tooth	50.19N
RP #2	Front left tooth	50.65N
RP #3	Front left tooth	99.45N
RP #4	Left incisor	150.53N
RP #5	Left incisor	200.62N
RP #6	Left incisor	200.83N
RP #7	Front right tooth	250.50N
RP #8	Front right tooth	250.77N
RP #9	Front right tooth	300.34N
RP #10	Front right tooth	351.36N

6.1.1 Instron Test Results

These preliminary RP specimen tests were conducted to assess how well the specimens were held in the rig. Tests were conducted with increasing load applications to assess if the specimen or rig were damaged or the specimen and housing slipped in the rig. Figure 31 shows how the system was set up for the testing with the alignment of the impactor with the individual tooth to be loaded.

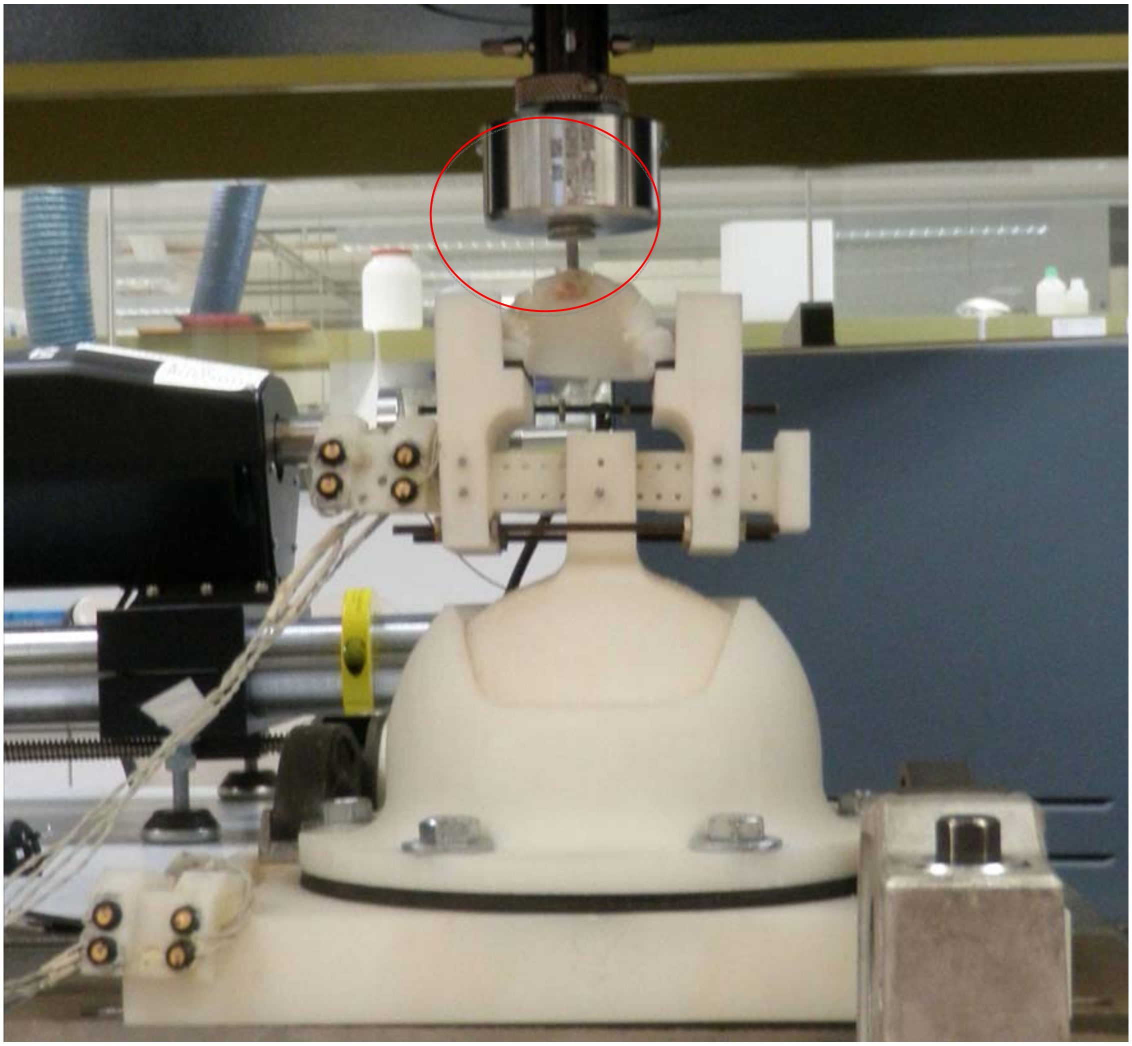

Figure 31 Alignment of the housing and specimen for loading of the front left tooth.

Ten RP specimen tests were successfully performed at increments of 50N from 50N to 350N, showing loading up to 350N was possible. During the tests it was clear from the data traces that the Instron machine was able to detect deflection in the system. An example of this is shown by the nonlinearity seen in the graph for RP Test 10 (Figure 32).

Based on these Instron results alone however, a distinction between whether the deflection occurred in the test rig or of the RP specimen was not able to be determined. These results highlighted the need for additional investigations using the Optotrak Marker system.

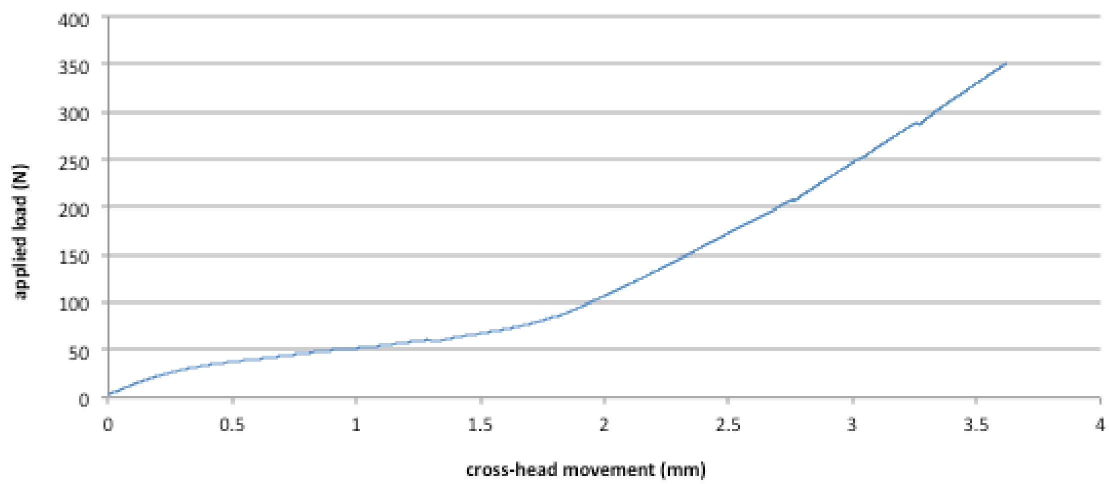

Figure 32 Instron machine results for RP Test 10, showing load delivered successfully to 350N, and nonlinearity of the applied load vs. cross-head movement plot suggesting deflection in the system.

6.1.2 Optotrak Marker Results

Three groups of Optotrak markers were put in place on the Instron cross-head, the test rig base plate, and the peg of the specimen housing, as was done in the pilot wooden block study. Two additional groups of markers were attached to the RP maxilla bone via nail insertion, and to the underside of the RP tooth to be tested. The five marker groupings are shown in Figure 33. As the integrity of the tooth was vital to testing, the markers needed to be fixed to the underside of the tooth in a non permanent, non destructive manner. To do this a nail was embedded into the top of the rapid prototyped rig and using dental cement, fixed to the underside of the tooth (Figure 34).

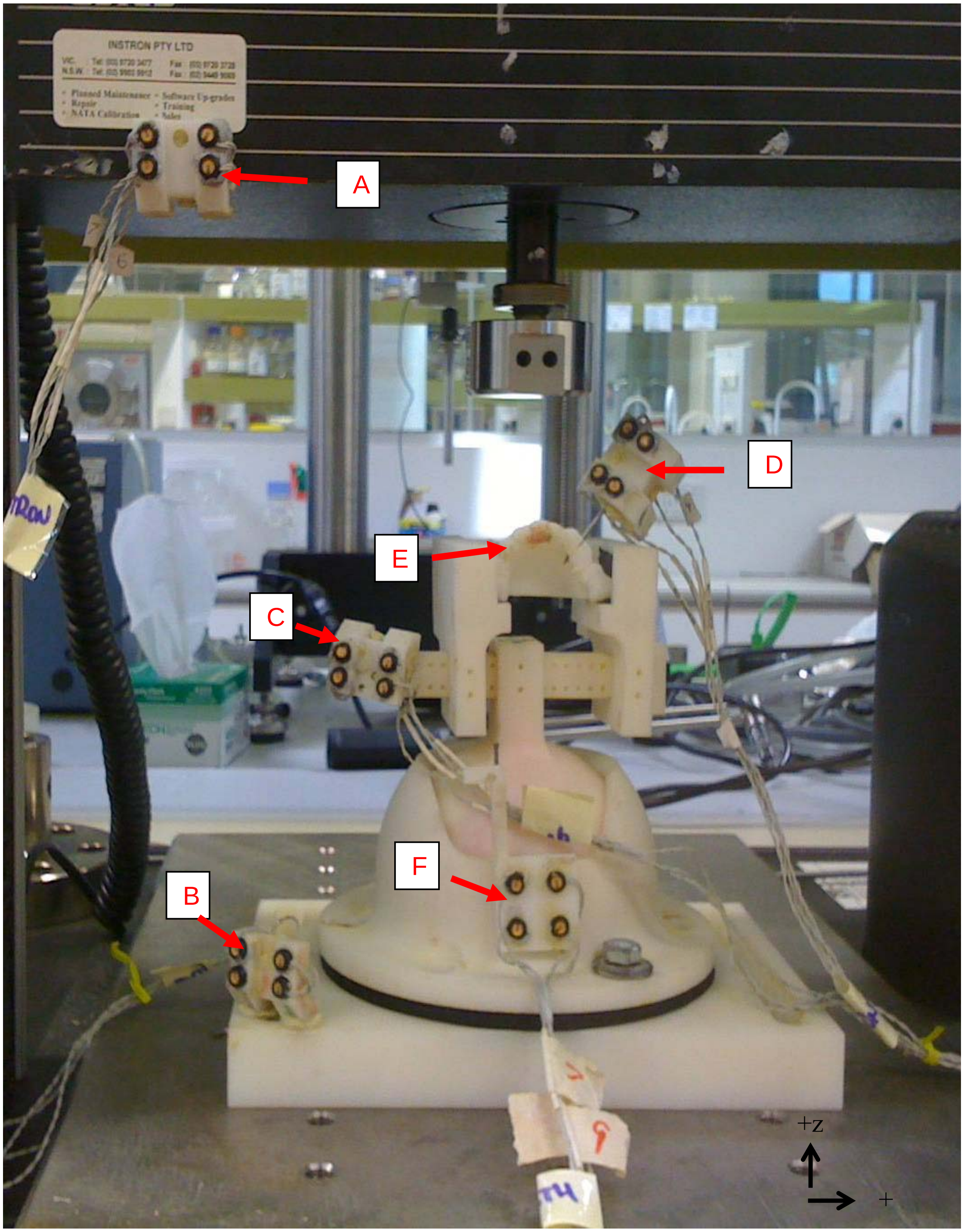

Figure 33 Placement of the five Optotrak marker groups: A, Instron machine cross-head; B, test rig base plate; C, test rig peg; D, maxilla bone specimen; E, place for attachment of the marker rig to the tooth being tested; F, marker rig for individual tooth (not attached to the underside of the tooth in this image. Note, the F marker would be attached to the tooth where the pink dental ceramic paste can be seen at E in the picture).

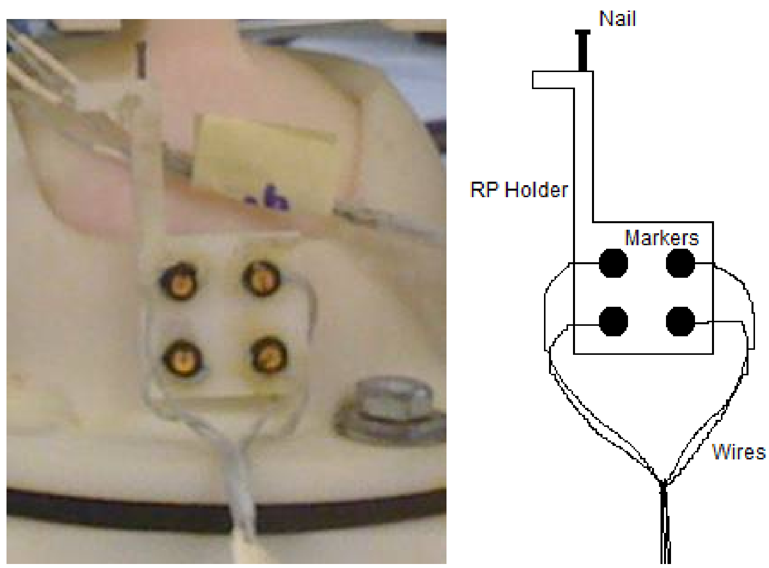

Figure 34 Photograph and drawing depicting the original RP tooth marker rig. ‘F’ in **Figure 33**.

The bone marker was inserted into the RP bone section of the maxilla to make sure the markers were in the receiver’s line of sight prior to beginning testing. The test set up showing positioning of the Instron machine and Optotrak scanner is shown below in Figure 35. Once it was deemed that the markers could be fixed to the bone in a non destructive temporary but firm manner, and seen by the Optotrak receiver, the bone markers were removed. They were not utilised during the RP tests as it was deemed there would be no independent motion of the tooth with respect to the bone for the RP samples.

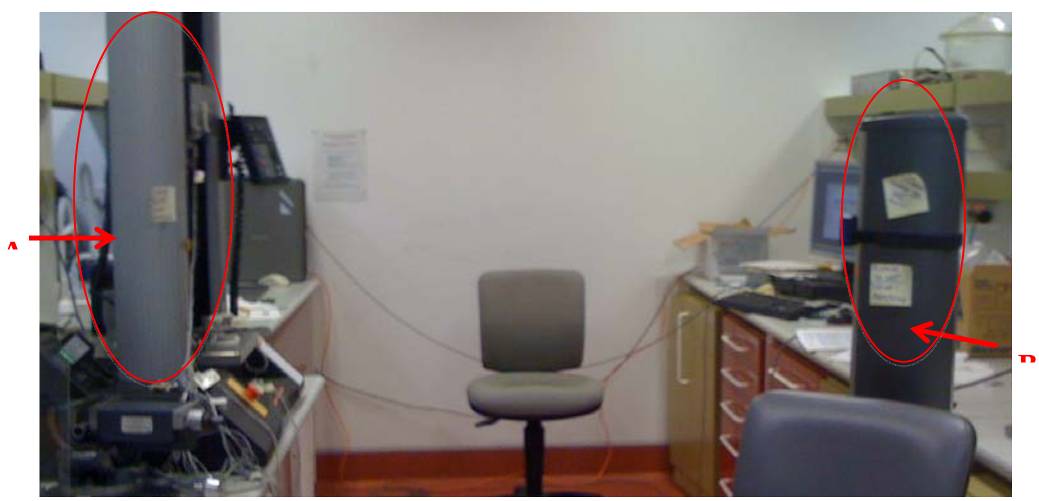

Figure 35 Test set up showing positioning of A. - Instron machine on left; and B. – Optotrak scanner on right.

A few issues arose with the Optotrak markers tracking the tooth motion early on in the RP testing. The weight of the RP rig, markers and cords combined kept moving the nail head within the dental cement on the underside of the tooth. Additionally, the length of the RP rig meant the bottom of the holder and the cords were impacting the ball section of the housing, interfering with the free motion of the holder. Hence, after the first three tests the RP rig was replaced with a block of wood (Figure 36). Unfortunately, the Optotrak scanner required a minimum of 1.5 meters distance between the receivers and the markers being captured. Due to limited space in the allocated work area in the test lab, the scanner therefore had to be placed at a slight angle, as opposed to perpendicular to the test rig. This resulted in slight motion being captured in all three directions during all tests performed, rather than just the desired linear displacements in the vertical direction. Best attempts have been made to reduce this effect when discussing results throughout this report. *Note: All Optotrak marker results have had their initial positions zeroed for consistency. Only the averages of the 4 marker sets have been presented here. Where there were not at least three markers visible in a marker set by the Optotrak receiver, the data point was not averaged. Smoothed line scatter plots are depicted for all Optotrak traces presented in the graphs below.*

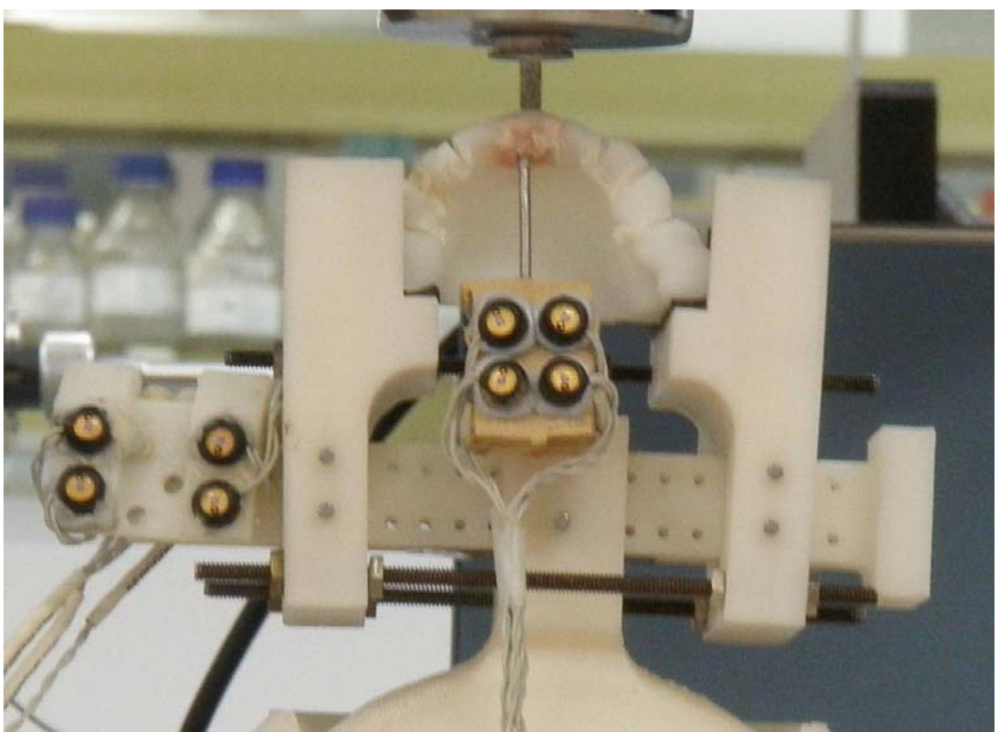

Figure 36 The wooden holder for the tooth markers that replace the RP rig, fixed to the underside of the tooth specimen via dental cement.

Once adjustments were made during the first few tests of the Optotrak marker traces for the test rig, the Optotrak results proved capable of capturing the desired points (Figure 37, Figure 38) and tracking their movement during testing.

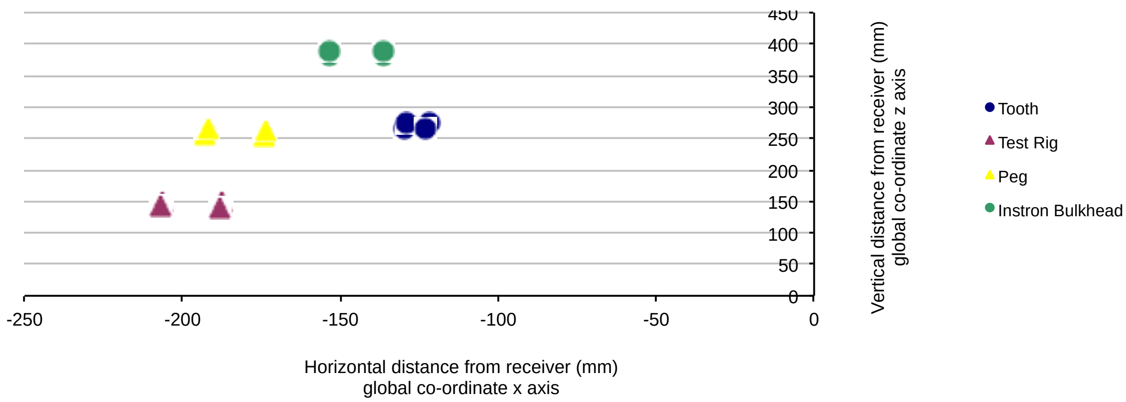

Figure 37 Optotrak marker setup representation of initial position before data was zeroed captured by Optotrak scanner for RP Test 9, showing placement of 4 tooth markers, 4 test rig markers, 4 peg markers and 4 Instron cross-head markers, corresponding to A, B, C and E in **Figure 33**.

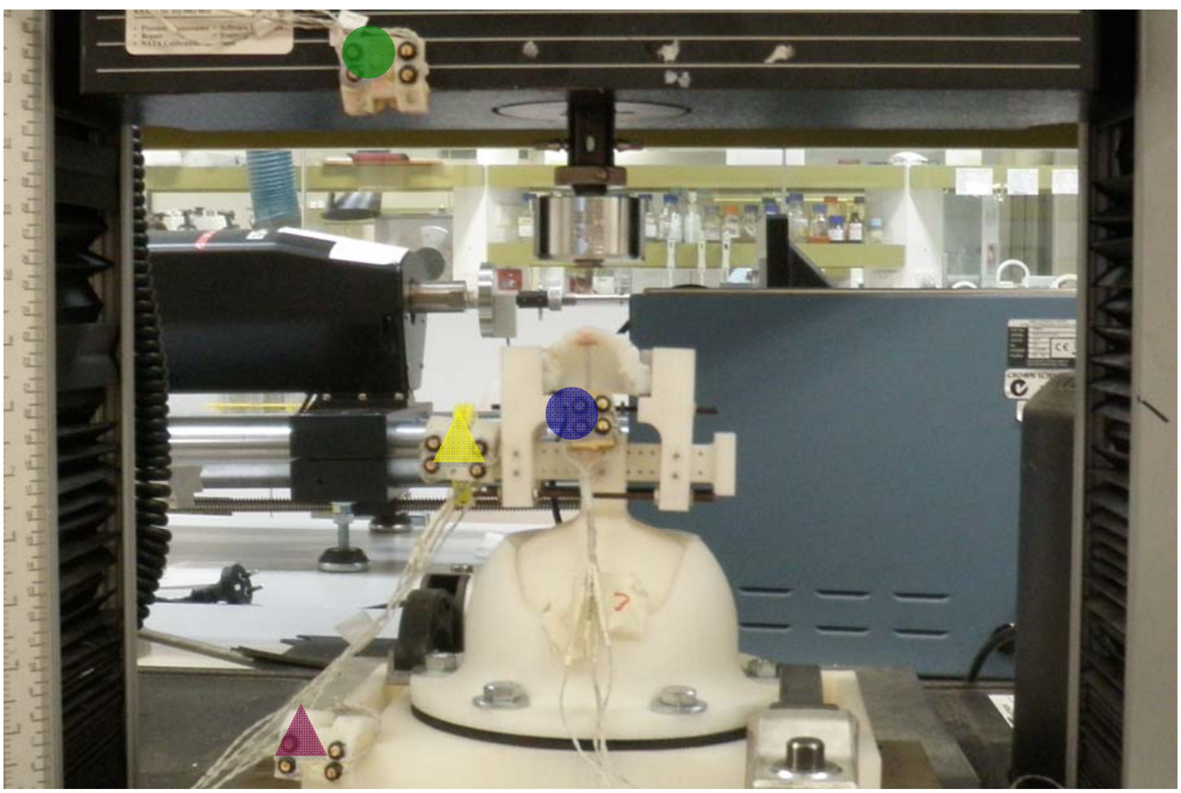

Figure 38 Positioning and set up of Optotrak marker sets for PMHS testing with wooden block tooth rig. Green - Instron cross-head; blue – tooth; yellow – peg; and red - test rig (refer t**o Figure 37Error! Reference source not found.**). Note the photograph is taken standing directly in line with the test rig set up. The Optotrak scanner and receiver were positioned angled and slightly to the left of where the photograph was taken due to space restrictions.

The Instron cross-head motion depicted by the Optotrak markers during RP Test 9 is shown below (Figure 39). As with the Instron results, the Optotrak marker traces show nonlinearity in the motion of the cross-head in the direction of applied force, suggesting there was deflection of the system.

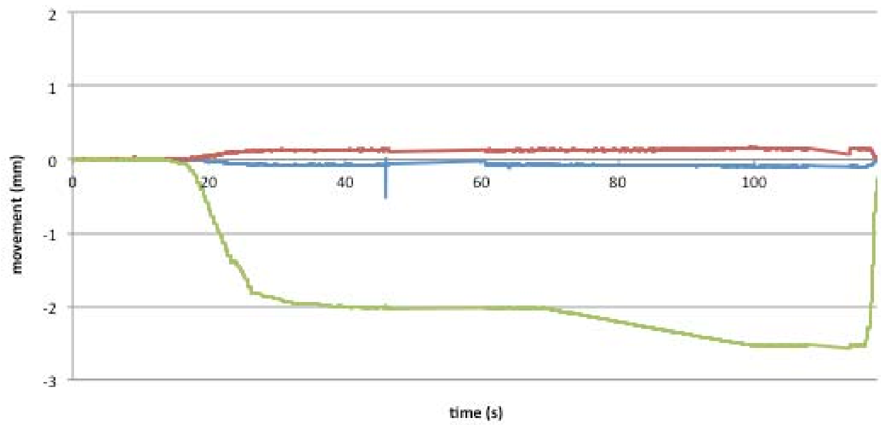

Figure 39 Optotrak marker traces (zeroed) for the Instron cross-head vertical motion (green), horizontal motion (blue) and fore/aft motion (red) motion during RP Test 9.

The motion depicted by the additional test rig, peg and tooth markers used during the tests allow for further investigation on the cause of the deflection. Examples of successful test rig, peg and tooth motion tracking from RP Test 7 are shown below. The test rig marker traces showed little movement throughout the test as expected (Figure 40**Error! Reference source not found.**), indicating there was no deflection of the system transmitted through to the base plate of the test rig.

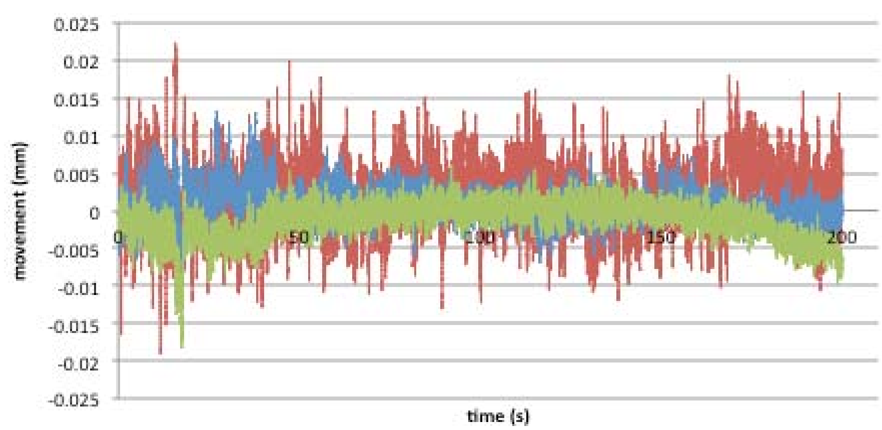

Figure 40 Optotrak marker traces (zeroed) for Test Rig marker vertical motion (green), horizontal motion (blue) and fore/aft motion (red) during RP Test 7.

The motion of the peg markers in all three directions (Figure 41) indicates there was deflection of the peg under loading of up to 0.5mm, indicating some flex in the housing and upper portion of the test rig as a result of the applied load.

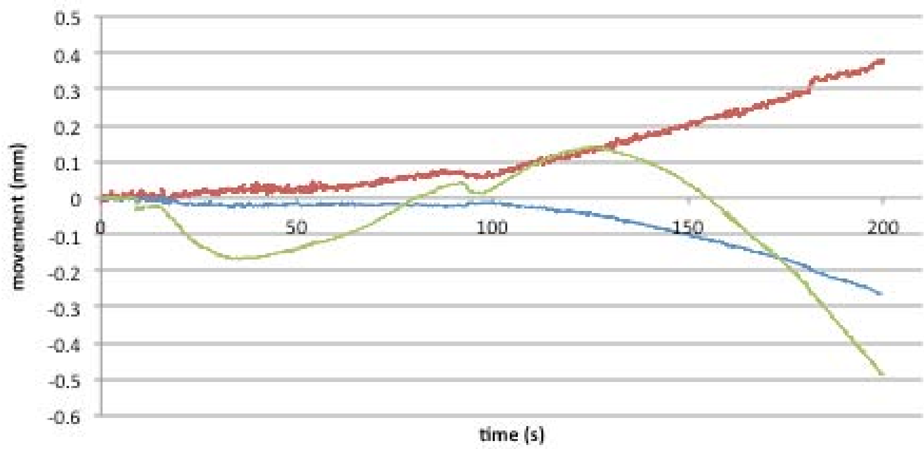

Figure 41 Optotrak marker traces (zeroed) for Peg marker vertical motion (green), horizontal motion (blue) and fore/aft motion (red) during RP Test 7.

The tooth marker traces showed clear distinct movement downwards of 3.56mm, in line with the expected motion as a result of the applied load (Figure 42). The Optotrak results allowed for analysis of the tooth movement relative to the peg deformation, and resulting tooth actual movement was recorded at 3.07mm (Figure 43). Despite the obvious trace of the tooth moving downwards, there was still however movement seen of the tooth within the housing, depicted by the motion traces in the horizontal and fore/aft planes.

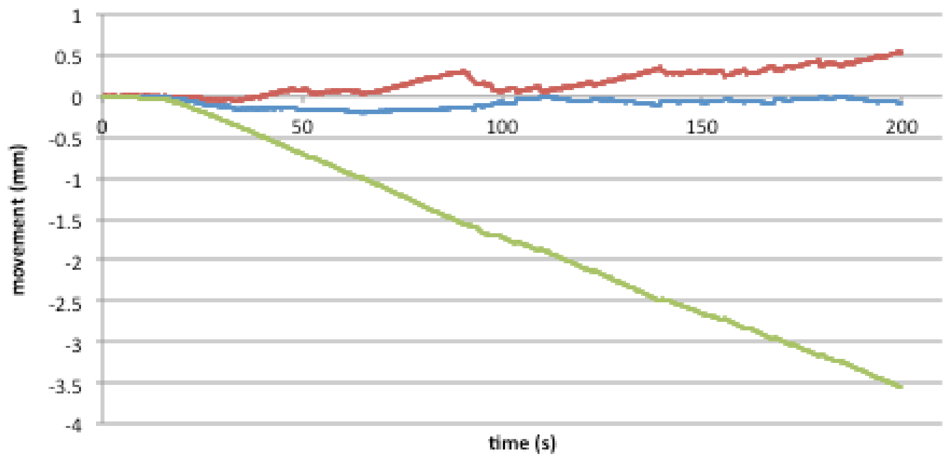

Figure 42 Optotrak marker traces (zeroed) for Tooth marker vertical motion (green), horizontal motion (blue) and fore/aft motion (red) during RP Test 7.

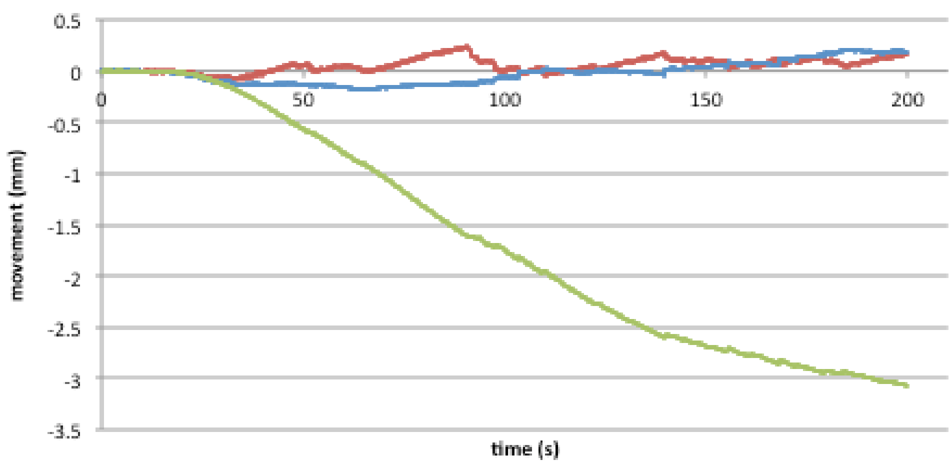

Figure 43 Motion of the tooth relative to the peg in the vertical direction (green), horizontal direction (blue) and fore/aft direction (red) during RP Test 7.

6.1.3 Rapid Prototype Testing Conclusions

In conclusion, the RP testing was a success for the following reasons;

- It confirmed that the Instron could deliver a quasi-static, direct frontal load as desired to an individual tooth specimen.
- It confirmed that the housing could be aligned to allow the tooth specimen to be presented to the impactor.
- It demonstrated that the results from the Instron machine identified when a slippage in the system occurred, thus allowing for force assessment of tooth and dentition mechanics.

- It demonstrated that the Optotrak Markers could successfully measure movement at a resolution needed to assess tooth motion.
- The Optotrak marker traces identified when a slippage occurred in the system, thus able to confirm the Instron data, and could help to decipher whether the slippage was between the specimen and housing, or whether there was movement of the housing itself. It is, therefore, predicted that the Optotrak markers will also be able to measure motion of the tooth with respect to the bone, thus allowing for assessment of tooth compliance.

Although many aspects of the testing proved successful, the RP tests did reveal that there was ‘give’ in the system, and that the stiffness of the RP material used in the test rig and specimen housing was susceptible to movement under the loads being delivered. However, as these deflections were small and the movement of the tooth was to be measured relative to the bone the system was deemed adequate for its purpose.

The testing also revealed that there could be motion of the specimen within the housing, indicating the fixation method was not adequate for this RP sample. This knowledge was used for more thorough inspection of the specimen in the housing before testing in the PMHS tests. It was expected that the change from RP material to biological material would allow for a better fit and moulding of the specimen within the housing when clamped into place, and subsequently stop this slippage from occurring.

6.2 Post Mortem Human Subject Testing

Before presenting the human specimen testing and results it is important to highlight again some of the known problems associated with testing biological specimens.

Post Mortem Human Subjects (PMHS) available for use in studies like this are often of an age not representative of the general sporting population. The specimens available for use at the time of testing were elderly subjects with some degree of osteoporosis present, which will have an affect on the strength of the specimen. Age also has an affect on the biomechanical response of the periodontal ligaments and the tooth’s supporting structures, which will have an affect on the compliance of the specimen. These were explained earlier in Sections 2.3 to 2.5.

The subjects used in this study were embalmed with Genelyn Anatomical Mix, administered through a normal arterial embalming process. The effects of embalming on the mechanical properties of the dentition are unknown, however it is generally accepted that embalming results in softer bones and laxer but stiffer ligaments. The literature supporting this is outlined earlier in Section 3.4.

6.2.1 Collection, Preparation and Scanning of PMHS Specimens

Three specimens were selected as described in Section 6.1. For all three PMHS test specimens, the cadaveric maxilla and dentition were excised with the help of a professional anatomical technician to minimise damage to the specimen. To visually determine and quantify the amount and condition of the dentin and enamel, the root, the PDL, the gum and the alveolar bone non-destructively before testing, the specimen was prepared for Micro CT scanning. Preparation included removing any object which may have caused artefact in the scan such as fillings, and trimming the specimen to a size to fit snuggly in the Micro CT canister to eliminate movement during the scanning process. An excised specimen is shown before and after preparation for scanning in Figure 44, and in the micro CT canister in Figure 45. After excision and between testing, the specimens were stored in PBS solution (Phosphate Buffered Saline) and refrigerated to help preserve their condition. During testing, to ensure the specimens were kept hydrated, they were wrapped in cloths soaked in the PBS solution.

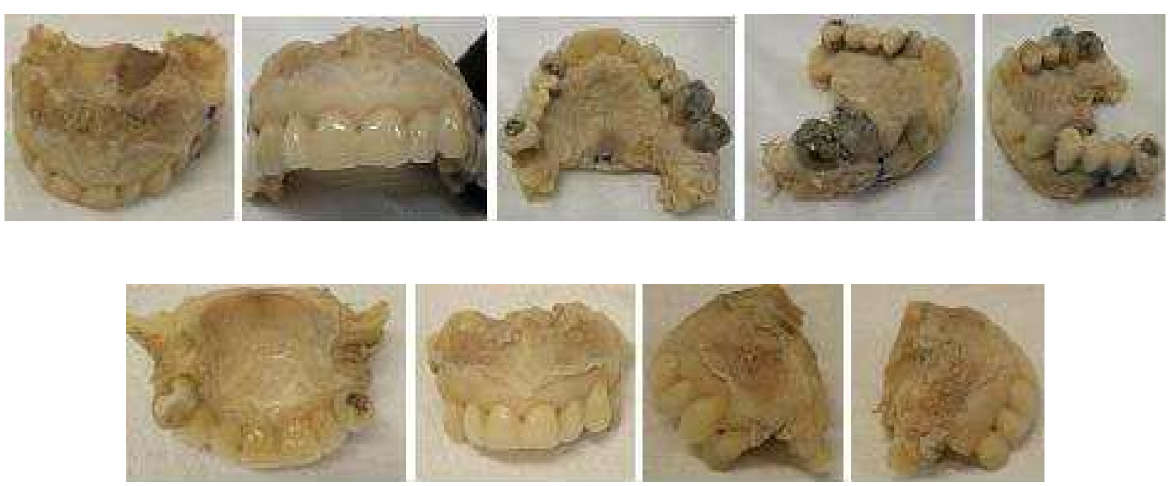

Figure 44 (Top) Views of the excised, unprepared maxilla. (Bottom) Views of the excised, prepared maxilla to allow insertion into micro CT canister after removal of fillings and bridges.

Figure 45 Insertion of the maxilla specimen into the micro CT canister.

Images from the micro CT scans of PMHS specimen 1 before testing are shown in Figure 46 and Figure 47. These images reveal it is possible to assess the size and structure of the tooth and root, and the alveolar bone present in the maxilla; as well as the proportion of enamel to dentin, and size and condition of the PDL in the specimens through micro CT scanning. This enabled valuable insight into the condition of each sample, and allowed for visualisation and quantification of any disruption or damage to the hidden structures of the tooth sustained during testing. It also allowed for visualisation of fractures to the tooth that are unable to be seen with the naked eye.

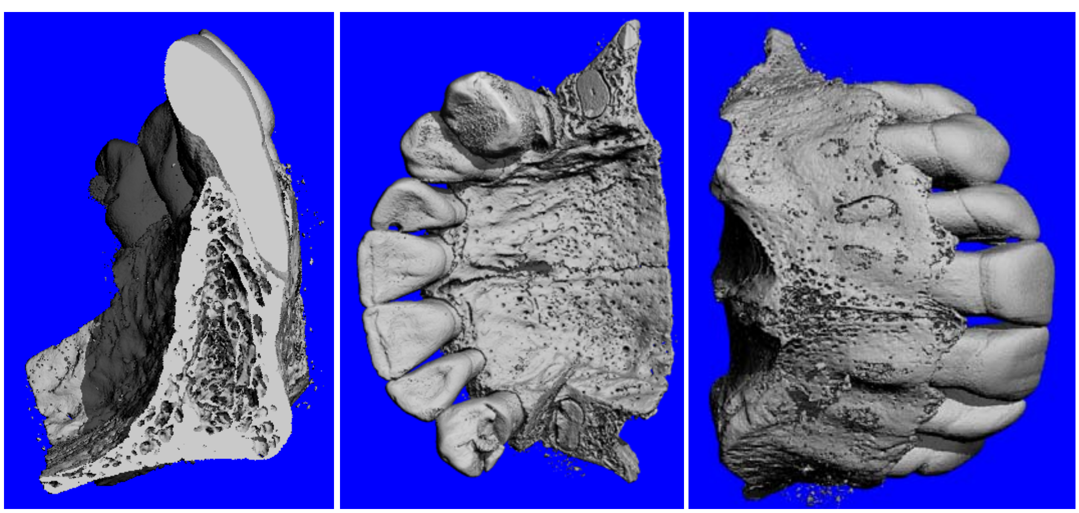

Figure 46 Example 3D images generated by the micro CT scan for PMHS specimen 1 pre testing.

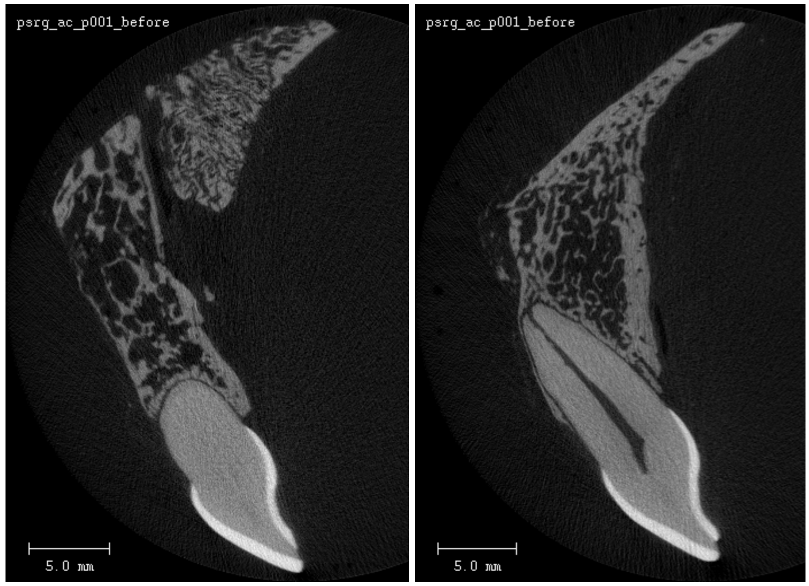

Figure 47 Example cross sectional images of the micro CT scan for PMHS specimen 1 pre testing.

6.2.2 Summary of PMHS Testing

The PMHS test protocol based on the previous RP tests, is shown in Appendix A. Appropriate personal protective equipment (PPE) was worn during the tests including eye protection, gloves and coveralls. The specimen housing was lined with cling wrap before insertion of the maxilla specimen, to protect the test rig from contamination.

As with the RP tests, the PMHS tests were performed by first preloading the tooth to 5N to ensure there was contact between the impactor and the specimen in the desired location at the centre of the frontal surface of the tooth being tested. As with the RP test, alignment was performed visually to locate the centre of the tooth's frontal surface and to position the tooth's surface perpendicular to the impactor. Quasi-static loading was delivered at a cross-head speed of 1mm/min via the Instron machine for PMHS specimen 1, and then increased to 3mm/min for PMHS specimen 2. A test matrix of nine selected PMHS tests performed is shown below in Table 9.

Table 9 Post Mortem Human Subject Tests

Test Number	Impacted Tooth	Peak Applied Force	PMHS specimen
PMHS 1	Front left tooth	17.53N	Specimen 1
PMHS 2	Front left tooth	0.11N	Specimen 1

PMHS 3	Front left tooth	50.04N	Specimen 1
PMHS 4	Front right tooth	43.66N	Specimen 1
PMHS 5	Front right tooth	74.3N	Specimen 1
PMHS 6	Front right tooth	91.91N	Specimen 1
PMHS 7	Front right tooth	65.21N	Specimen 1
PMHS 8	Front right tooth	114.38N	Specimen 2
PMHS 9	Front left tooth	158.96N	Specimen 2

For PMHS Tests 1 to 4, the Instron was programmed to halt the test when a quasi-static load of 50N had been reached. For PMHS Tests 5 to 7, the Instron was programmed to halt the test when a quasi-static load of 100N had been reached. Unfortunately, the majority of tests performed failed to give complete sets of results due to one or more of the following reasons:

- movement of the specimen in the test rig,
- slippage of the impactor on the tooth surface, or,
- interference with the Optotrak markers;

requiring the Instron to be manually halted when the load plateaued or suddenly dropped off. As such, for PMHS Tests 8 and 9, the Instron was not programmed to halt at a pre-defined load, but rather was stopped manually when the load appeared to plateau out, based on the real time tracking of the Instron force traces.

Despite the loading issues outlined above, no obvious visual damage was seen to any of the teeth or maxilla specimens during the tests. The test results and descriptions of the tests and modifications made with each trial to combat the issues are included in more detail below.

An example of the test set up for the PMHS tests is shown in Figure 49 and the Optotrak markers captured by the scanner in Figure 48. The placement of tooth and bone markers was done so movement of the tooth could be measured relative to the maxilla and movement of the specimen in the rig assessed by movement of the bone relative to the test rig peg. *Note: All Instron data is presented as recorded from the machine. As with the RP Tests, all Optotrak marker results have had their initial positions zeroed for consistency. Only the averages of the 4 marker sets have been presented here. Where there were not at least three markers visible in a marker set by the Optotrak receiver, the data point was not averaged. Smoothed line scatter plots are depicted for all Optotrak traces presented in the graphs below.*

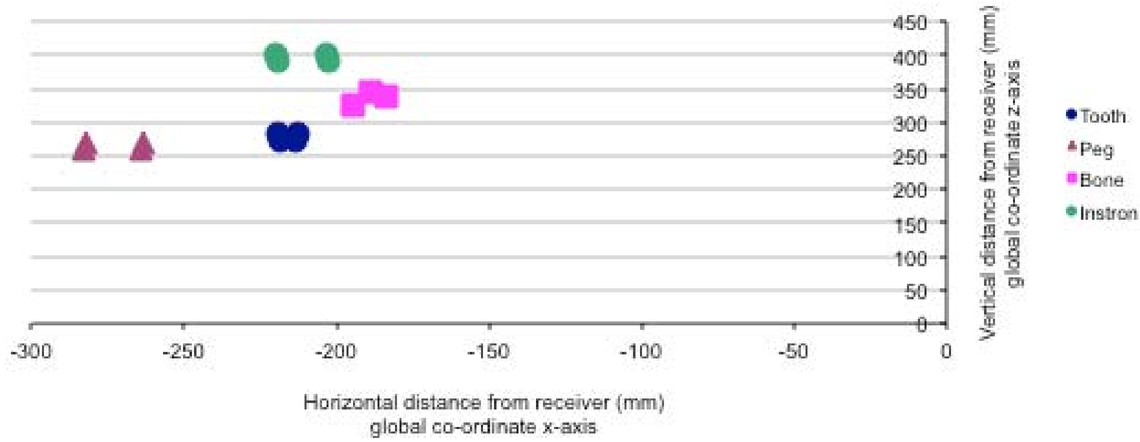

Figure 48 Optotrak marker setup representation of initial position before data was zeroed, captured by Optotrak scanner for PMHS Test 3, showing placement of 4 tooth markers, 4 test rig markers, 4 peg markers and 4 Instron cross-head markers corresponding to the set up shown in **Figure 49**. This marker set up was used for all specimen 1 PMHS tests.

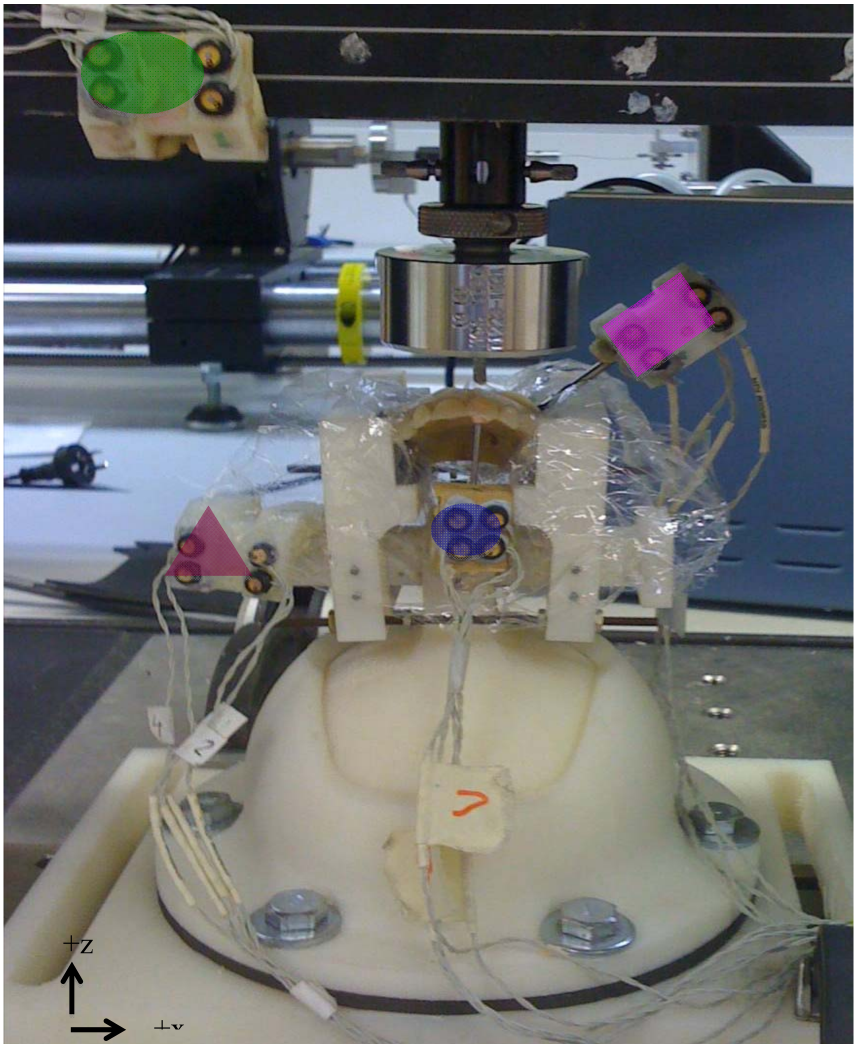

Figure 49 Test set up for PMHS Tests, showing placement of the maxilla specimen and the attachment of the Optotrak marker sets for Instron cross-head (green), maxilla bone (pink), tooth (blue) and peg (red). Refer to **Figure 48**.

6.2.3 PMHS Specimen 1 Testing

PMHS Tests 1 to 3 were performed on PMHS specimen 1 on the front left tooth. PMHS Tests 4 to 7 were performed on PMHS specimen 1 on the front right tooth. Photos of PMHS specimen 1 aligned for loading pre Test 1 and Test 4 are shown in Figure 50. A close up view of the specimen in the test rig is shown in Figure 51. The bone marker rig was inserted into the maxilla on the left hand side away from the loaded tooth and the tooth marker was secured via dental cement to the underside of the tooth (Figure 49). As mentioned above, the majority of tests performed failed to give complete sets of results due to issues with the stability of the specimen in the housing, and or the coupling between the impactor and the tooth's surface.

Between PMHS Tests 2 and 3, investigations were performed on improving the coupling between the impactor and the tooth's surface. The impactor was realigned slightly a number of times in an attempt to find a section of the tooth surface where slippage did not occur. Unfortunately the impactor continued to slip off the surface of the tooth. The tooth surface was cleaned with bleach in an attempt to remove any possible residue the PBS solution had left on the tooth that may have been contributing to the slip, but this made little difference. As a result, the decision was made to place a small amount of dental cement on the surface of the tooth to allow better interaction between the impactor and the tooth, stabilising the tooth to impactor interface (Figure 50 and Figure 51). The specimen was placed back in the housing and the test rig clamped and secured as per previous tests. The impactor was then aligned with the tooth and the dental cement placed directly under where the impactor was to make contact on the tooth surface. The impactor was lowered slightly to make a light impression in the dental cement before it set. This dental cement and procedure was used from PMHS Test 3 onwards, and for the remainder of the tests performed on PMHS specimen 1 and 2.

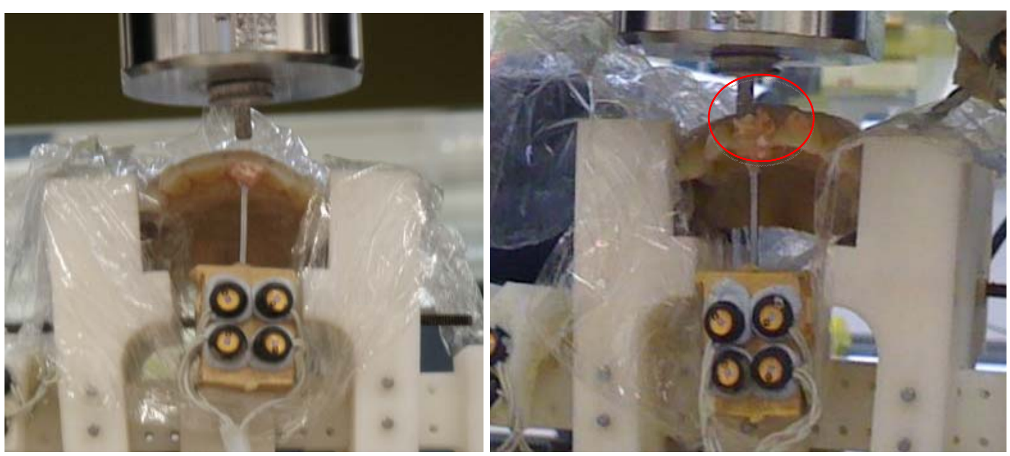

Figure 50 Alignment of the impactor with the centre of the front left tooth surface for PMHS Test 1, (left) and Impactor alignment with centre of the front right tooth surface for PMHS Test 4 (right). Note presence of Optotrak tooth markers attached to the underside of the tooth to be loaded via dental cement (both pictures), and dental cement on the tooth's frontal surfaces for Test 3 and test 4 (circled on the right).

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Figure 51 PMHS specimen 1 in test rig ready for testing, showing attachment of markers to underside of tooth, and markers inserted into maxilla bone segment.

The Instron results for the PMHS specimen 1 tests were able to detect;

- when deflection in the system occurred, evident by lack of consistent, steady increasing load vs. displacement traces of the Instron cross-head during loading (Figure 52),
- movement of the specimen within the housing, evident by dips in the load vs, displacement traces such as in PMHS Test 3 at approximately 0.9mm cross-head displacement and 26N applied load, and in PMHS Test 5 at approximately 1.3mm cross-head displacement and 30N applied load (Figure 52), and
- slippage of the impactor off the tooth's surface, which was a new occurrence in the PMHS testing, evident by sharp recurring drop offs in the load such as seen at the end of the traces for PMHS Tests 5, 6 and 7 (Figure 52).

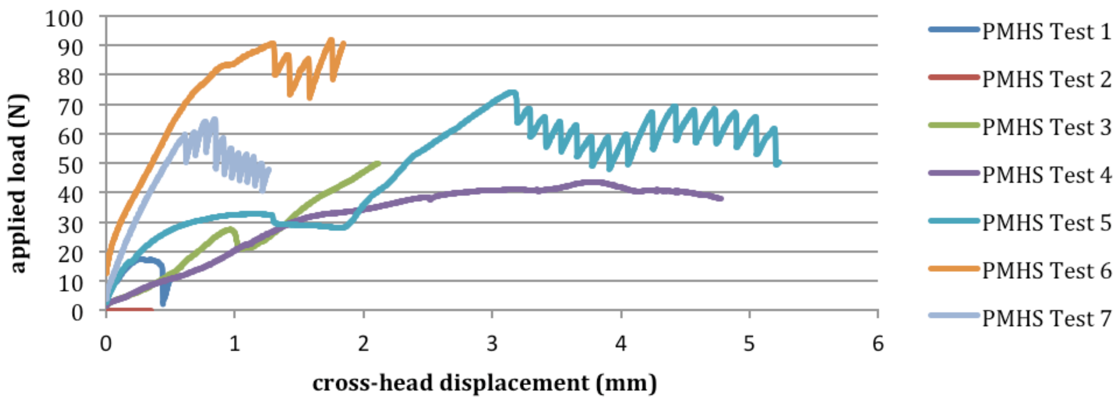

Figure 52 Instron results for PMHS specimen 1 tests, showing a) lack of consistent, steady increasing load traces indicating deflection in the system for the majority of tests, b) small dips in the traces indicating movement of the specimen within the housing (most noticeable in tests 3 and 5), and c) sharp drop offs in the load indicating slippage of the impactor on the tooth surface (seen at the end of test 5, 6 and 7 traces).

The slippage of the impactor on the tooth's surface could also be seen visually, and although it can be hypothesised the slippage was occurring due to a change in presented angle of the tooth's surface, it could not be determined by visual assessment or Instron results alone whether the movement was a result of luxation of the tooth, or rotation of the whole specimen in the test rig housing.

The only PMHS test that showed no signs of impactor slippage or specimen instability in the Instron results was PMHS Test 4. However, after a load of approximately 43N was delivered and the cross-head had moved approximately 5mm the load appeared to plateau, and the desired full 50N load was not able to be delivered to the tooth (Figure 52).

PMHS Test 5 showed a distinct plateau section in the Instron's load vs. displacement curve at approximately 30N with the cross-head displacement continuing from approximately 1.3mm to 2mm, after a small drop off of the applied load (Figure 52). It is hypothesised that this load plateau suggests movement of the specimen in the test rig to a more stable position, until esentially the testing began again and the load was applied to the tooth at a slightly different angle at a steady rate until the maximum load for the test was reached at 74.3N and slippage of the impactor on the tooth surface occurred.

Due to the instability seen during PMHS Test 5, the specimen was re-mounted and re-clamped in position, and the Optotrak markers were removed and reinserted on the tooth's underside and in the maxilla bone segment prior to PMHS Test 6.

The greatest load applied to a tooth during testing on PMHS specimen 1 was during PMHS Test 6, with the Instron recording a maximum applied load of 91.9N (Figure 52). This 91.9N load is below the tooth's force tolerance limit of 120-220N suggested in the previously revised literature.

The Optotrak marker traces for PMHS specimen 1 tests successfully highlighted the capability of the Optotrak system to detect the small movements seen in the specimen and test rig during this kind of quasi-static loading. Furthermore, they were able to clarify where instability was seen in the system when it occurred, and to what degree. The markers were also capable of allowing for independent motion of the tooth with respect to the maxilla to be determined and measured, which in turn allowed for load deformation curves to be generated for the tooth and it's supporting structures as an intact system.

More specifically, the Optotrak markers placed on the Instron cross-head were able to identify the movement of the cross-head during the preloading of specimens to 5N, allowing distinction of the motion during pre-testing and during actual testing. For all PMHS tests, linear motion was noted in the direction of the applied load (Figure 53). Small motion was recorded in the horizontal and fore/aft directions however as it was due to the orientation of the Optotrak scanner being at an angle to the test rig as opposed to the desired perpendicular placement as mentioned earlier it has not included here.

The jump in the marker trace at approximately 40 seconds for PMHS Test 6 (Figure 53) indicates the specimen moved during testing. This was not depicted in the Instron results.

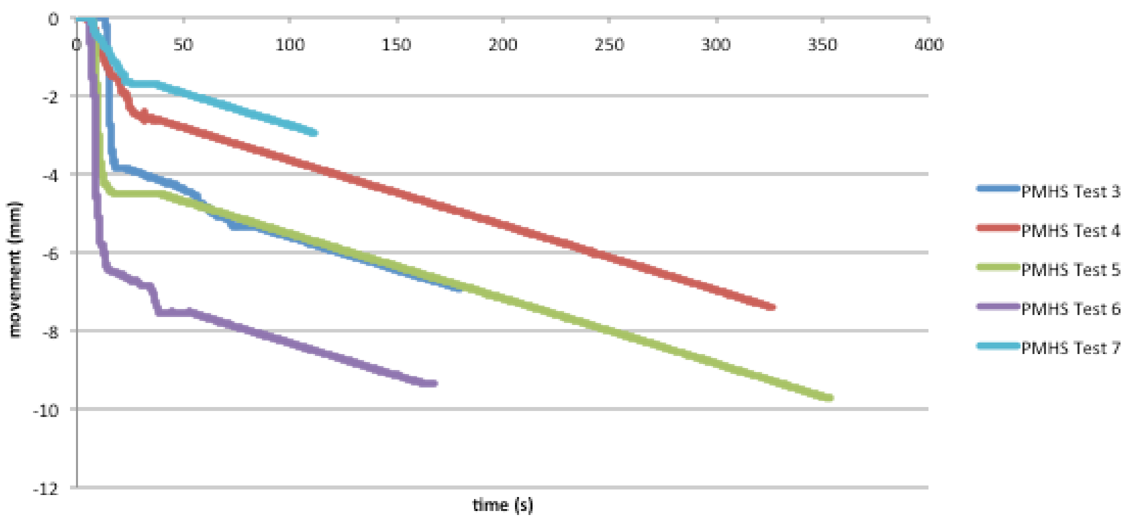

Figure 53 Optotrak marker traces (zeroed) for Instron cross-head motion in the direction of applied load during PMHS specimen 1 tests.

As with the RP tests, the Optotrak markers when positioned on the test rig base during PMHS specimen 1 tests, confirmed there was no deflection of the system transmitted through the test rig past the ball and clamping ball sleeve.

The Optotrak markers placed on the peg clearly showed when there was deflection of the peg under the applied load, indicating there was flex in the RP housing and test rig. Although this information could be gathered from the Instron results, the markers could quantify the amount of motion. In all the PMHS specimen 1 tests, the largest motion was recorded in the direction of the applied load, between 0.1mm and 1.0mm, however motion was often seen in the horizontal and fore/aft directions also. On the whole, there was little movement of the peg markers in comparison with the movement seen in the maxilla bone segment and the tooth markers. An example of the Optotrak markers tracking the motion of the peg is shown for PMHS Test 4 (Figure 54).

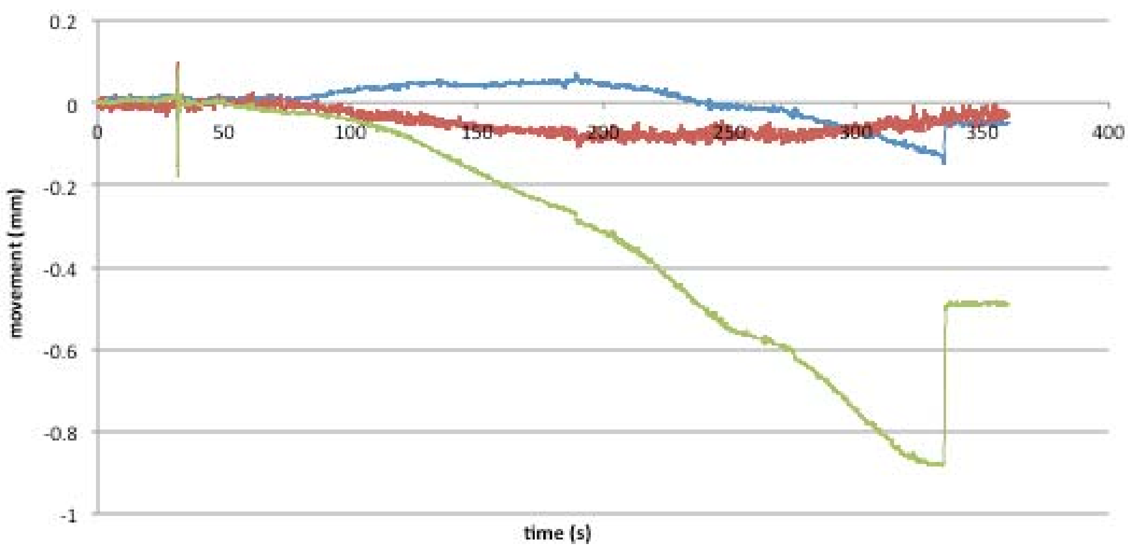

Figure 54 Optotrak marker traces (zeroed) for Peg vertical (green), horizontal (blue) and fore/aft (red) motion during PMHS Test 4. Note the steady movement seen in the direction of applied load indicating flex of the RP test rig under the applied load.

The Optotrak markers tracking the maxilla bone segment showed movement in all three directions (vertical, horizontal and fore/aft) up to 2mm in Test 3, 4mm in Test 4, 1.5mm in Test 5, 2.2mm in Test 6, and 1.5mm in Test 7, indicating as expected, that these marker traces were capable of showing obvious signs of failures in the system, including:

- slippage or movement (rotation) of the specimen in the housing, evident by increasing motion in the horizontal and or fore/aft directions;
- contact between the impactor and bone marker rig during downward motion of the Instron cross-head, evident by a linear increase in motion in the horizontal and vertical directions; and,
- unsteady placement of the marker rig in the maxilla specimen, possibly due to the pin hole stretching under the weight of the markers on the rig, or the change in temperature

of the specimen as a result of testing time, evident by unsmooth, ‘jumpy’ looking traces with increased noise appearing in the data points.

An example of the Optotrak markers tracking the motion of the maxilla bone segment is shown for PMHS Test 4 (Figure 55).

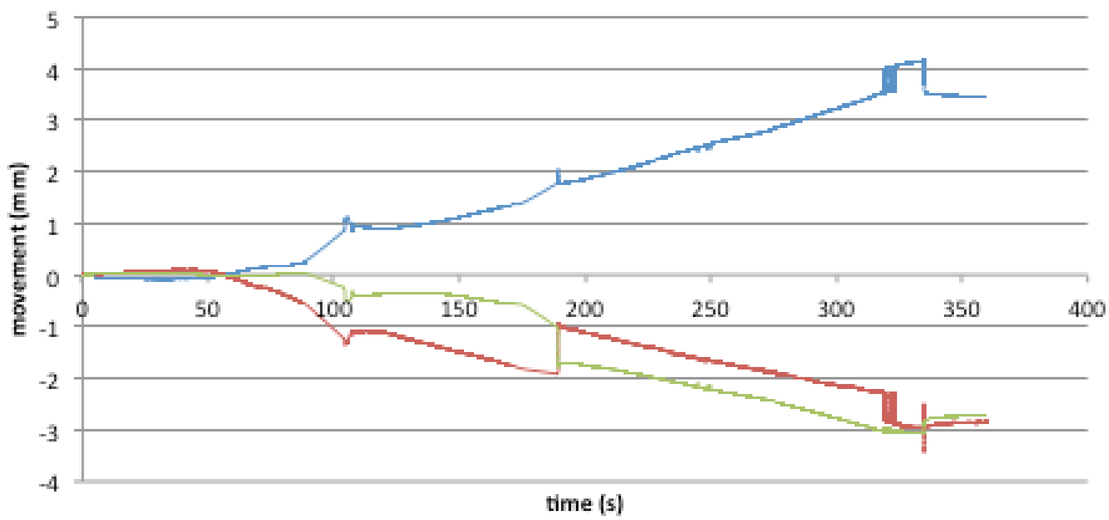

Figure 55 Optotrak marker traces (zeroed) for maxilla bone segment vertical (green), horizontal (blue) and fore/aft (red) motion during PMHS Test 4. Note the large motion seen in the horizontal direction indicating contact between impactor and bone marker rig, and the irregular jumps and movement in the traces indicating instability of the specimen in the housing and or marker rig in the maxilla bone segment.

Additionally, often a number of the bone markers flickered out of sight during the PMHS tests (in particular PMHS Test 5), making it hard to accurately trace the motion of the bone throughout the test. Although only very small motions were being measured thus theoretically the markers should have remained in view, it is hypothesised that as the receiver was positioned at an angle to the test rig to achieve the 1.5m distance between markers and receiver, any slight backward rotation of the markers would put the markers behind the test rig and or impactor thus interrupting the line of sight with the receiver.

The Optotrak markers attached to the underside of the tooth consistently recorded steady motion in the direction of applied load until some failure of the system occurred, at which point the traces helped identify if the failure was related to the tooth itself or the system as a whole. During PMHS Test 3, a steady increase in motion to a maximum movement of 1.79mm in the direction of applied load was noted, with less than 0.3mm of movement detected in the horizontal and fore/aft directions. Although both the Instron results and the bone marker results for PMHS Test 3 suggest movement of the specimen within the housing, the tooth marker traces didn't seem to indicate this when looked at by themselves. During PMHS Test 4, a steady increase in motion was again seen, this time to a maximum movement of 5.68mm in the direction of applied load, with less than 1mm of movement detected in the horizontal and fore/aft directions. An example of the Optotrak markers tracking the motion of the tooth is shown for PMHS Test 4 (Figure 56).

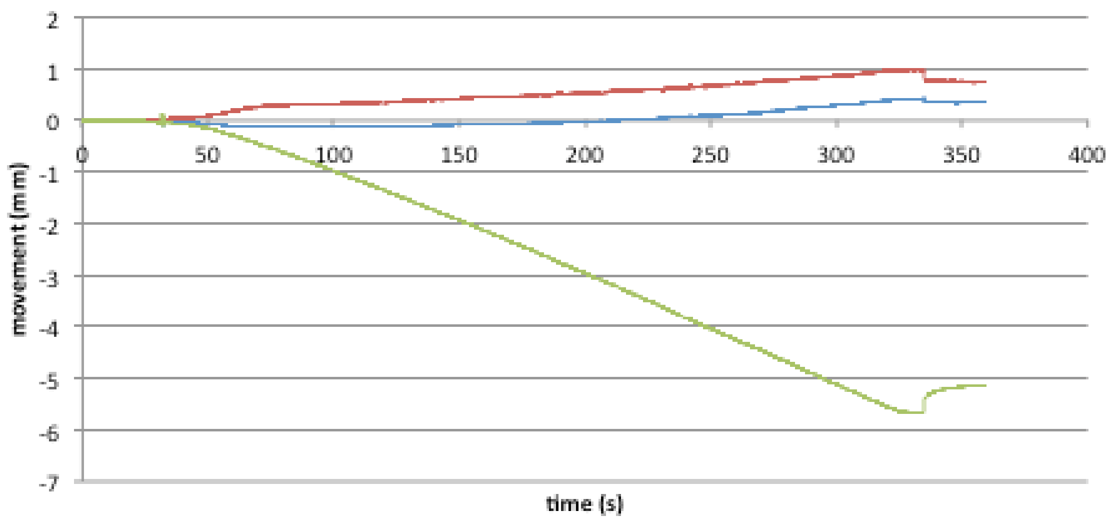

Figure 56 Optotrak marker traces (zeroed) for tooth vertical (green), horizontal (blue) and fore/aft (red) motion during PMHS Test 4.

PMHS Test 5 initially also showed a steady increase in motion to a maximum movement of 2.2mm in the direction of applied load, with less than 0.5mm movement in the other directions. The movement of the tooth then appears to plateau out for a period of time, before then showing noticeable movement (1 to 2mm) in the horizontal and fore/aft directions, indicating either that the tooth markers also picked up movement of the specimen in the housing, and/or that luxation of the tooth may have occurred. Either way, it highlighted instability in the system.

The tooth markers in PMHS Test 6 and PMHS Test 7 followed similar traces to that seen in Test 5, however on a smaller scale, with maximum movement of 0.3mm and 0.2mm in the direction of applied load before plateau (Tests 6 and 7 respectively), and then 0.2mm to 0.8mm and 0.4mm to 0.8mm in the horizontal and fore/aft directions after plateau (Tests 6 and 7 respectively). During PMHS Test 6 the tooth markers showed a larger movement in the fore/aft direction than downwards movement after plateau, and showed less motion overall than the bone markers, indicating the whole specimen had rotated in the test rig as opposed to the tooth having moved within it's socket. Thus, it is hypothesised that the section of tooth trace after plateau was overwhelmed by the bone marker movement, and as such not considered a test of the tooth's mechanical characteristics.

To gauge the mechanical characteristics of the tested teeth more accurately, plots of the tooth marker movement minus the maxilla bone marker movement (i.e. the independent motion of the tooth relative to the bone) (Figure 57), and the load deformation curve of the tooth relative to the bone (Figure 58) were made. Only motion in the direction of the applied load was considered. It was anticipated that PMHS specimen 1 would be sent for post testing micro CT scanning at this point to assess any changes and/or damage to the hidden supporting structures after testing to support and/or help clarify the findings, however this unfortunately was not possible.

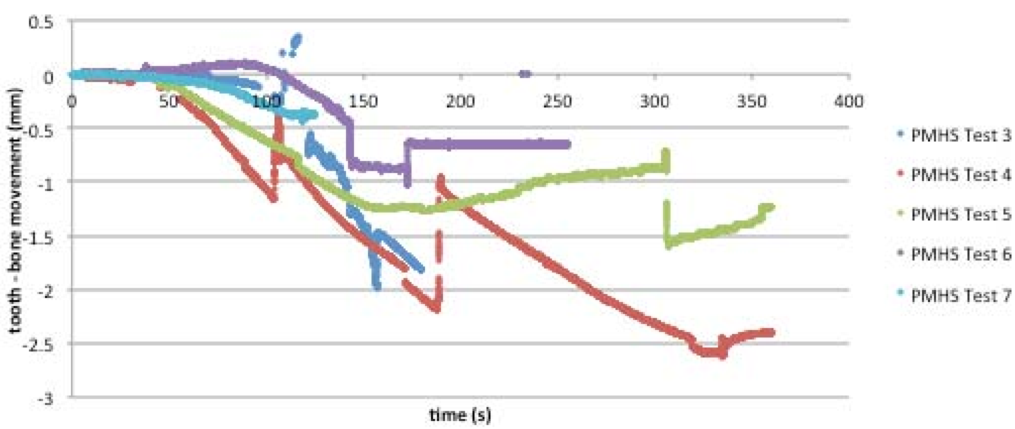

Figure 57 Independent motion of the tooth relative to the bone in the direction of applied load (as traced by the Optotrak markers) for PMHS Tests 3 through 7.

From the plots of the tooth marker movement minus the maxilla bone marker movement (Figure 57), it appears there was independent displacement of the tooth of approximately:

- 2mm during PMHS Test 3,
- 2.5mm during PMHS Test 4,
- 1.5mm during PMHS Test 5,
- 1mm during PMHS Test 6, and
- 0.5mm during PMHS Test 7.

The independent motion of the teeth seen in this study's testing is on the lower end of the deflection tolerance limit of 2-6mm for permanent injury suggested in the reviewed literature in Chapter 3. It is noted that for all PMHS tests, the marker traces of the tooth-bone motion more closely resemble the shape of the original bone marker traces than the original tooth marker traces, suggesting perhaps movement of the specimen within the housing did affect the tooth traces.

The load deformation plots (Figure 58), although to be considered cautiously due to the issues seen in the testing, provide a valuable insight into tooth compliance. Mainly, that the testing proposed and trialled in this study is capable of producing such information.

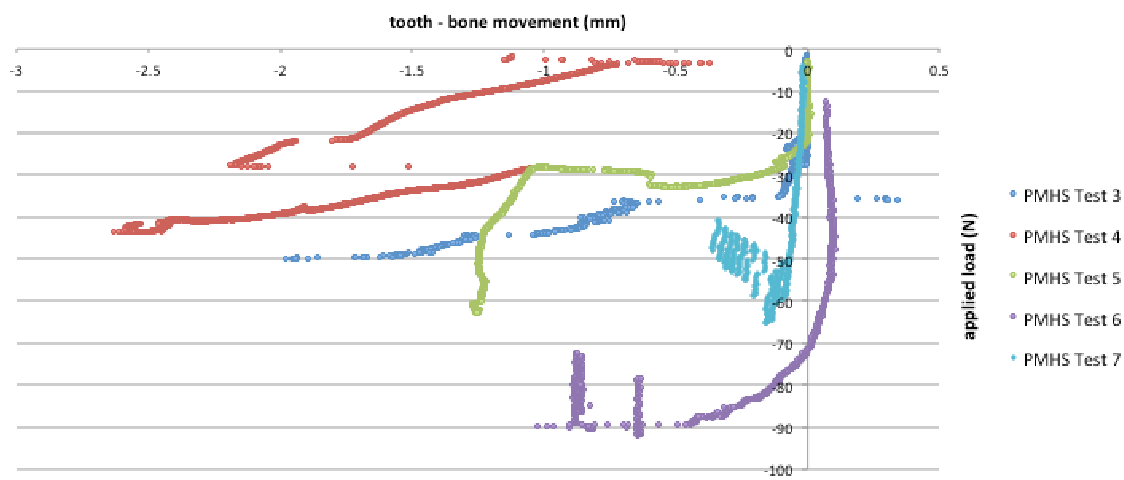

Figure 58 Load deformation curves for PMHS specimen 1 Tests 3 through 7, showing Instron applied load and tooth motion relative to the maxilla bone segment.

The load deformation curve for PMHS Test 3 suggests the front left tooth's supporting structures allow for 1.98mm of vertical movement of the tooth under a 50N load. It also indicates that displacement of the tooth did not begin to occur until a load of at least 30N was applied, suggesting there was no independent motion of the tooth which is consistent with the results in Figure 57. This could either be as a result of the initial portion of the test taking up the slack in the system until the specimen was secure in the housing, or could indicate that the tooth-bone interaction was initially stiff and the supporting structures began to give under a load of 30N.

The load deformation curve for PMHS Test 4 differs significantly from that seen in PMHS Test 3, with PMHS Test 4 showing movement of the front right tooth from the start of testing. At a load of approximately 30N, a shift in the tooth-bone markers from 2.2mm deformation to only

1mm deformation occurs very quickly (in the space of only a few data acquisition points) possibly suggesting the markers moved or the specimen moved within the housing at this point. As it occurred at around the 30N mark, where deformation began in PMHS Test 3, it is hypothesised that the initial part of the curve was movement taking up slack in the housing and flex of the test rig, and the more accurate indication of the tooth's mechanical characteristics are portrayed in the 30-45N section of the plot. This indicates the tooth's supporting structures allowed for approximately 1.6mm of vertical movement under a load of 45N.

The load deformation curve for PMHS Test 5 indicates that displacement of the tooth did not begin to occur until a load of at least 30N is applied, which is consistent with PMHS Test 3, and the hypothesis formed for PMHS Test 4. Test 5 however goes on to indicate the tooth moved approximately 1mm without much further load applied, and then only 0.2mm of movement under the next 44N of load suggesting during this section of the test the system was too unstable to accurately analyse (as also suggested in the Instron results, the Optotrak marker traces and the individual tooth and bone marker traces).

The load deformation curve for PMHS Test 6 suggests the tooth underwent 0.1mm of movement under a load 87N. However, this specimen showed an initial negative displacement, which may have been due to rotation of the whole specimen in the rig as mentioned previously.

The load deformation curve for PMHS Test 7 shows under 60N of load, the tooth moved 0.1mm, and then continued to move a further 0.25mm with no further increase in the load, both of which suggest the specimen was not sufficiently secured in the test rig to allow for pure loading to the tooth.

6.2.4 PMHS Specimen 2 Testing

PMHS Tests 8 and 9 were undertaken on specimen 2. Owing to movement of specimen 1 within the housing, and the slippage of the impactor on the tooth surface still occurring which was thought might be due to a change in angle of the tooth surface due to the movement of the specimen within the housing, PMHS specimen 2 was mounted on a flat metal plate with superglue (Figure 59), before being placed into the test rig. It was anticipated that this metal plate would allow for a flat, level, secure fitment of the specimen in the housing and allow for improved clamping of the specimen in place in the test rig.

Figure 59 PMHS specimen 2 attached to a metal base plate to allow for improved clamping of the specimen in the test rig housing.

Two additional wooden blocks were added to the test rig between the specimen housing and the ball and socket (Figure 60) to help reduce any flexing of the test rig that was occurring during the loading. As the arch length of PMHS specimen 2 was greater than that of specimen 1 the original RP Optotrak tooth holder was used for this specimen.

The bone marker was also moved from the left hand side of the maxilla to the right hand side, to aid in capturing all four of the markers with the receiver throughout the test, eliminating the line of sight issues seen in earlier testing.

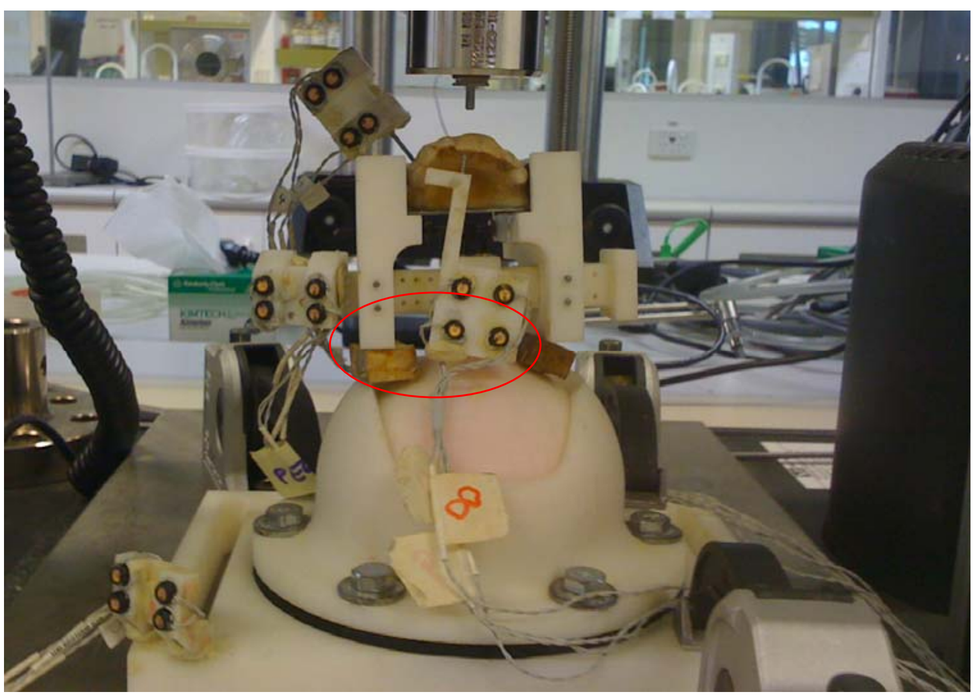

Figure 60 PMHS specimen 2 set up for testing, showing insertion of wooden blocks between housing and ball and socket joint (circled), and Optotrak marker placements.

It was hypothesised that increasing the loading rate from 1mm/min to 3mm/min may also aid in minimising the chance for the impactor to slip as the load would be delivered quicker, but could still be considered a quasi-static load as required in these initial test series.

PMHS Test 8 was performed on the front right tooth of specimen 2 and PMHS Test 9 was performed on the front left tooth (Figure 61). In both tests dental cement was again used on the loaded surface of the tooth. For these tests, however, the impactor tip was left in the dental cement while it set to ensure coupling between the impactor and the tooth. After testing the specimen and Instron attachment were removed from the test rig and Instron machine respectively, and the dental cement was carefully chipped off the tooth, then from around the impactor tip.

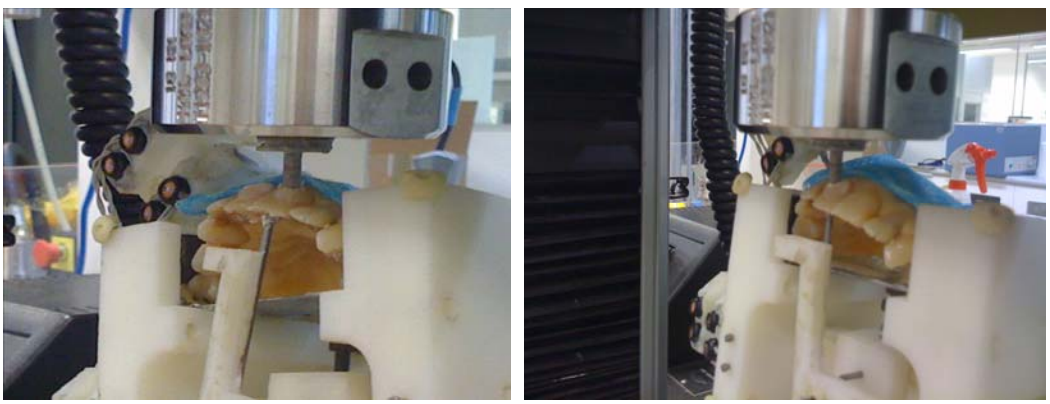

Figure 61 PMHS specimen 2 (left) testing on the front left tooth and (right) testing on the front right tooth.

The Instron results for PMHS Test 8 and PMHS Test 9 are shown in Figure 62. In both tests, steady increase in applied load is seen before the load drops off. There is no section of the curve that suggests slippage of the specimen or impactor as seen in previous tests, thus suggesting the tolerance limit of the specimen was reached. The front left tooth experienced a maximum load of 114.38N. The front right tooth experienced a maximum load of 158N. The Optotrak marker traces for test 8 and 9 support the Instron results showing a movement of 3.4mm of the cross head in Test 8 and 5.5mm in Test 9 (Figure 63).

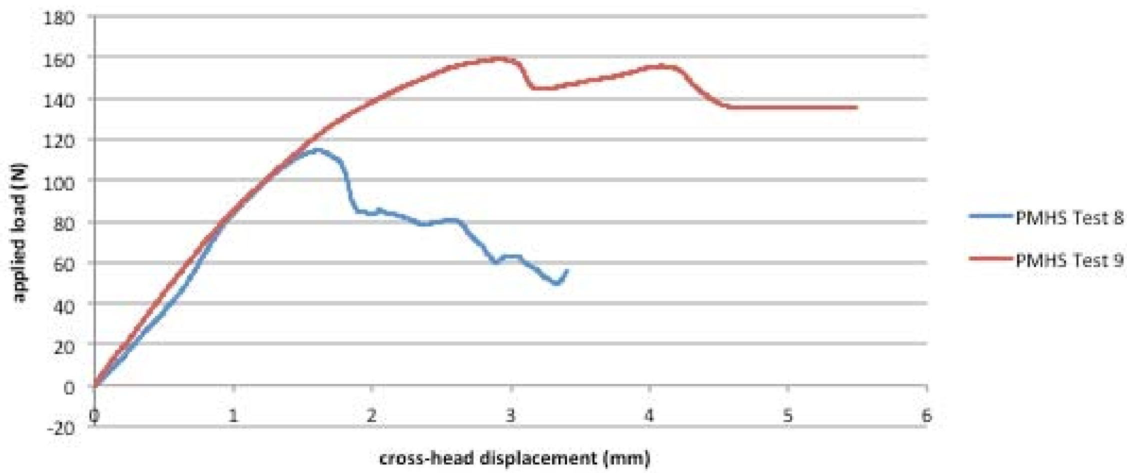

Figure 62 Instron results for PMHS Tests 8 and 9.

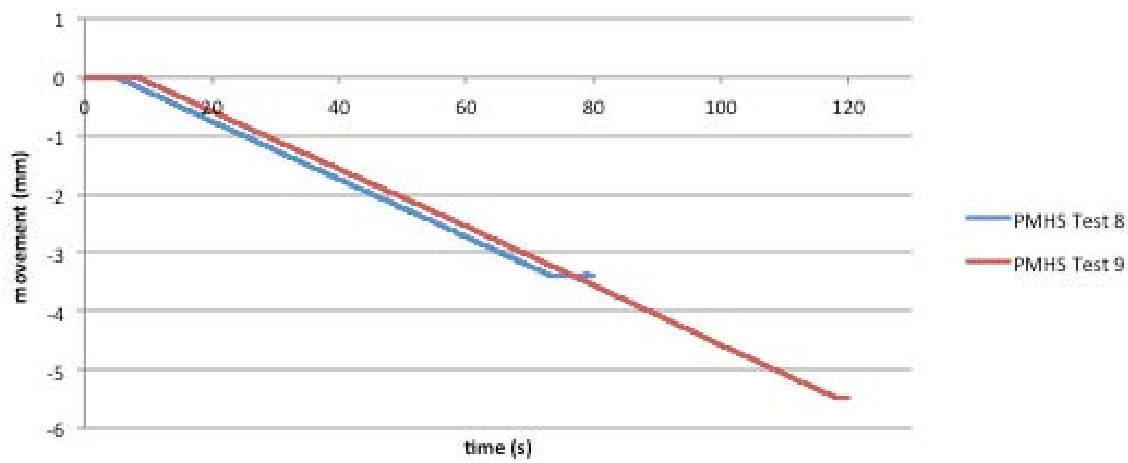

Figure 63 Optotrak marker traces (zeroed) for Instron cross-head motion in the direction of applied load during PMHS specimen 2 tests. Note the plateau at the end of the traces indicating when testing was stopped and the load being delivered was halted.

As there was no sign visually or in the Instron results of movement or damage to the specimen or test rig, even though the load failed to increase further, the testing was stopped. Although the teeth themselves showed no visible signs of cracking or fracture, or signs of luxation, it was possible that the PDL or alveolar bone had been damaged. The level of applied load reached in PMHS Test 8 and 9 (114N and 158N respectively) were on the lower end of the 120-220N tooth tolerance limit suggested in the literature [79]. Ideally at this point PMHS specimen 2 would have been sent for post test micro CT testing to assess whether any damage had occurred to the hidden supporting structures, unfortunately however this was not possible and the specimen was returned.

The lack of motion in the traces captured by the Optotrak peg markers during PMHS Test 8 and PMHS 9 showed that the placement of the two blocks of wood between the housing and ball and socket successfully prevented flexing of the peg and test rig under load. An example of the Optotrak markers tracking the motion of the peg is shown for PMHS Test 8 (Figure 64).

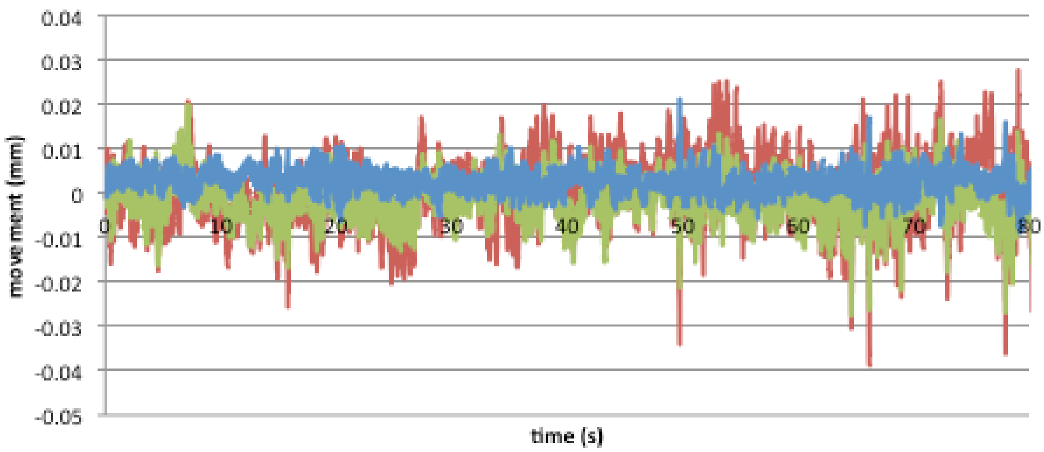

Figure 64 Optotrak marker traces (zeroed) for peg vertical (blue), horizontal (red) and fore/aft (green) motion during PMHS Test 8. Note the minimal amount of motion detected, indicating stability of the peg under load.

The reduction in motion seen in the bone marker traces in PMHS specimen 2 tests compared with PMHS specimen 1 tests, also showed that the attachment of the PMHS specimen to a metal plate aided in stabilising the specimen in the housing, enabling the load to be delivered directly to the tooth. Unfortunately however, during both PMHS Test 8 and PMHS Test 9 the Instron attachment came into contact with the bone marker rig during loading, pushing it to the left and loosening the nail within the maxilla. The contact does not appear to have affected the movement recorded in the direction of applied load, and although contact occurred, the markers remained within the line of sight of the Optotrak receiver throughout the tests. An example of the Optotrak markers tracking the motion of the maxilla bone segment is shown for PMHS Test 8 (Figure 65).

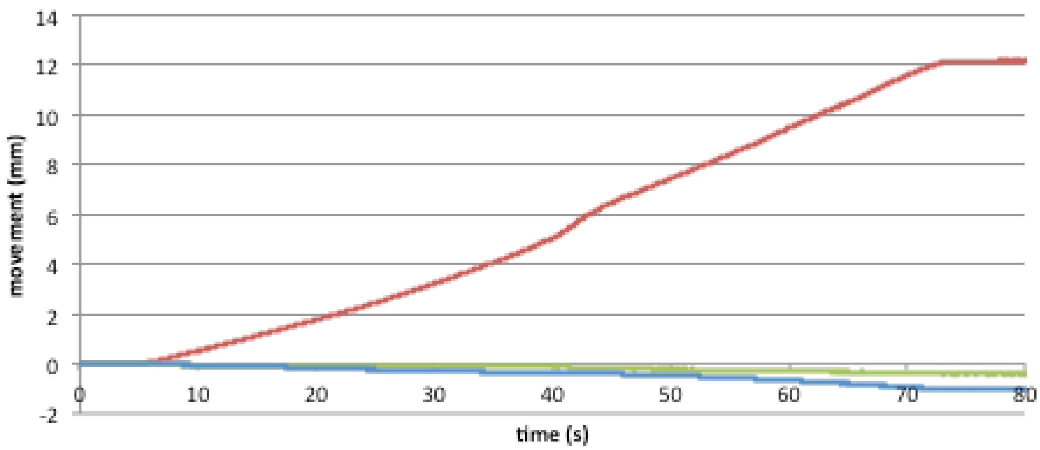

Figure 65 Optotrak marker traces (zeroed) for bone vertical (blue), horizontal (red) and fore/aft (green) motion during PMHS Test 8. Note the reduced motion seen in the vertical direction compared with earlier specimen 1 tests, indicating increased stability of the specimen in the housing, and the contact which occurred between the Instron attachment and the marker rig during testing, indicated by the linear motion tracked in the horizontal direction.

With the increased stability in the system and of the specimen in PMHS Tests 8 and 9, more detailed information on the motion of the tooth under load could be drawn from the tooth Optotrak marker traces. The tooth marker traces showed steady downward movement of just over 5mm for PMHS Test 8 (Figure 66) and 6.4mm for PMHS Test 9 (Figure 67), under the applied load, with very little movement seen in the horizontal directions indicating there was little to no sideways motion of the teeth during testing. The movement seen in the fore/aft direction in both tests correlated with the tooth rotating within the socket, confirming there was independent motion of the tooth relative to the bone in both cases. It is hypothesised that this tooth motion is indicative of luxation. At approximately 95 seconds into PMHS Test 9 a jump was seen in all traces suggesting there was give in the tooth's supporting structures.

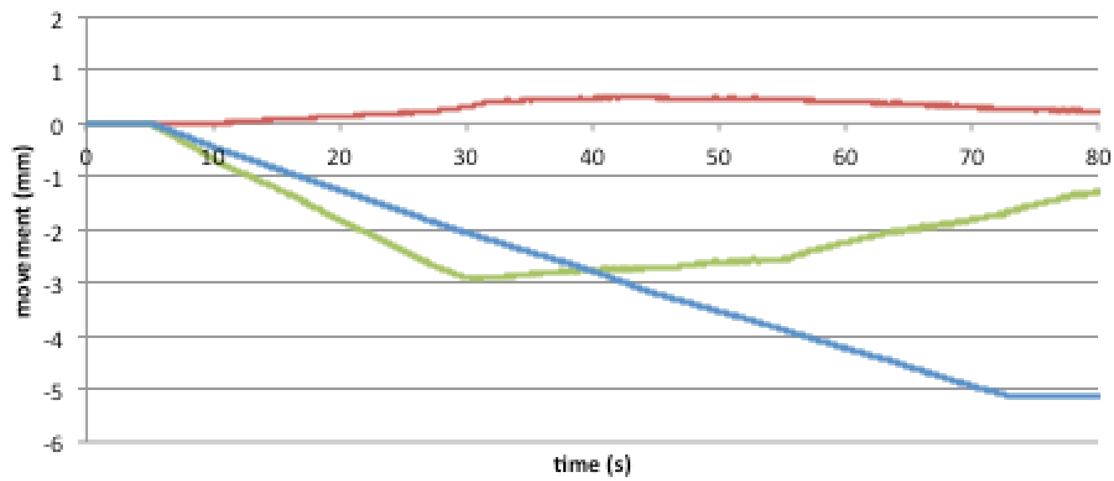

Figure 66 Optotrak marker traces (zeroed) for tooth vertical (blue), horizontal (red) and fore/aft (green) motion during PMHS Test 8. Note the steady motion in the direction of applied force indicated by the vertical trace, and the rotation of the tooth within the socket indicated by the motion seen in the fore/aft direction.

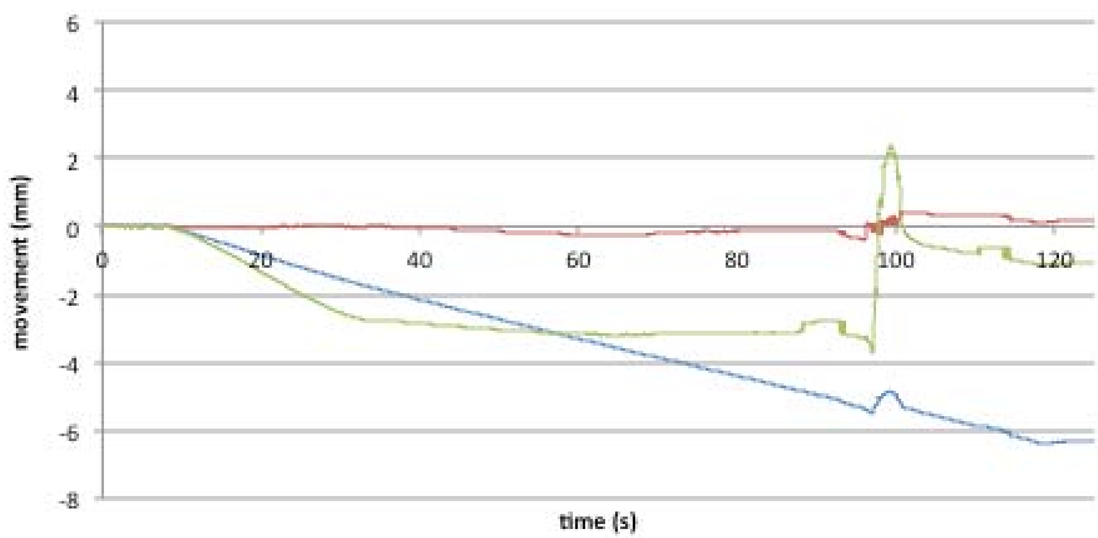

Figure 67 Optotrak marker traces (zeroed) for tooth vertical (blue), horizontal (red) and fore/aft (green) motion during PMHS Test 9. Note the steady motion in the direction of applied force indicated by the vertical trace, and the rotation of the tooth within the socket indicated by the motion seen in the fore/aft direction. The jump in the traces seen between 90 and 100 seconds suggests the tooth's supporting structures gave way.

Although there was little motion of the maxilla bone specimen, plots of the tooth motion relative to the bone in the direction of the applied load were generated for PMHS Tests 8 and PMHS Test 9 (Figure 68). These plots showed independent tooth motion of just over 4mm in PMHS Test 8, and 3.2mm in PMHS Test 9. From the plot of tooth independent motion, the jump in the trace noted at 95 seconds in PMHS Test 9 was assessed as 0.6mm.

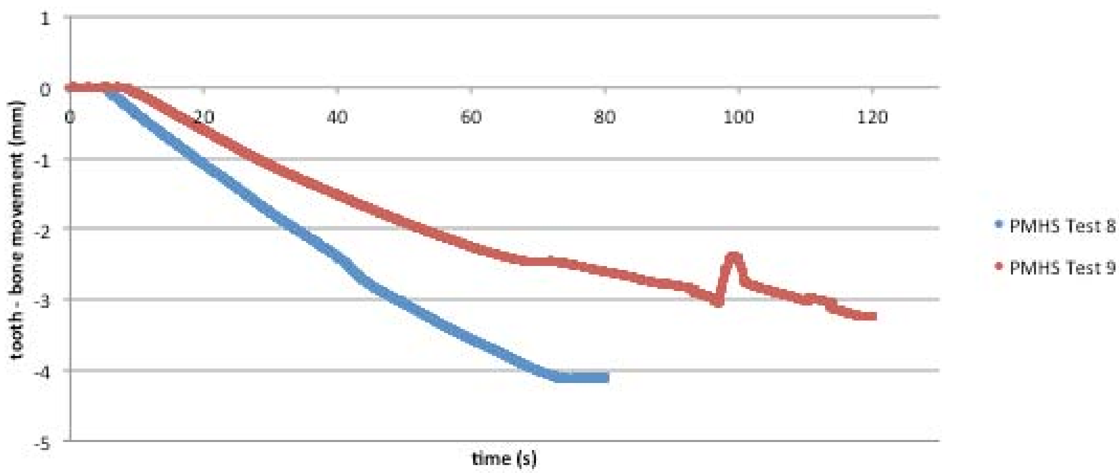

Figure 68 Independent motion of the tooth relative to the bone in the direction of applied load (as traced by the Optotrak markers) for PMHS Tests 8 and 9.

It is hypothesised that the jump in the trace suggests there was give in the tooth's supporting structures, which in correlation with the 6.4mm of movement in the direction of applied force, is in line with the deflection tolerance limit of 2-6mm for permanent injury suggested in the literature [63, 64, 90]. Damage of this kind was not visible to the naked eye during or after testing, and the only way to assess damage of the supporting structures without compromising the specimen would be to micro CT scan post test. Unfortunately, as with PMHS specimen 1, micro CT scanning post test was unavailable.

The load deformation curve for PMHS Test 8 (Figure 69) indicates the mechanical characteristics of the front right tooth of specimen 2 allow 2.3mm of vertical movement of the tooth under a load of 114N. The load deformation curve for PMHS Test 9 (Figure 69) indicates the mechanical characteristics of the front left tooth of specimen 2 allow for approximately 2.5mm of vertical movement under a load of 158N.

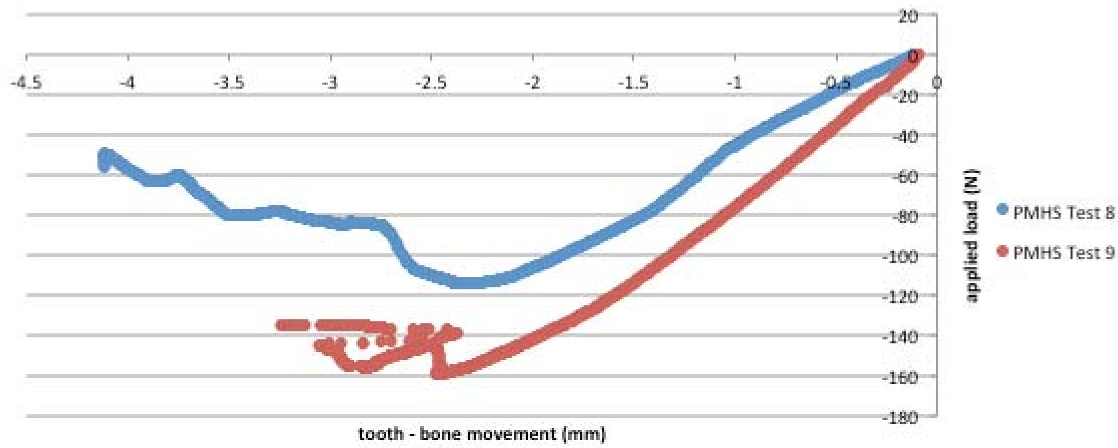

Figure 69 Load deformation curves for PMHS specimen 2 Tests, showing Instron applied load and tooth motion relative to the maxilla bone segment.

6.2.5 PMHS Specimen 3 Testing

Although full analyses of the data and scans had not yet been undertaken, PMHS specimen 3 had already been prepared and needed to be utilised before it was returned. As all the testing performed as part of this study was unique in nature and essentially a trial of a test method, test apparatus and testing capabilities, PMHS specimen 3 was used for trialling more options rather than for data collection, as it was not sure whether further testing along these lines would achieve anything further.

Between testing specimen 2 and specimen 3, an alternative Instron attachment (Figure 70) became available. The long narrow shape of this attachment was more suitable for use in the testing as it allowed for easier placement of, and less chance of interference with, the Optotrak bone marker holder. It allowed for the same tack shaped flat nail to be attached, and made it visually easier to line up the impactor with the presented tooth surface (Figure 71).

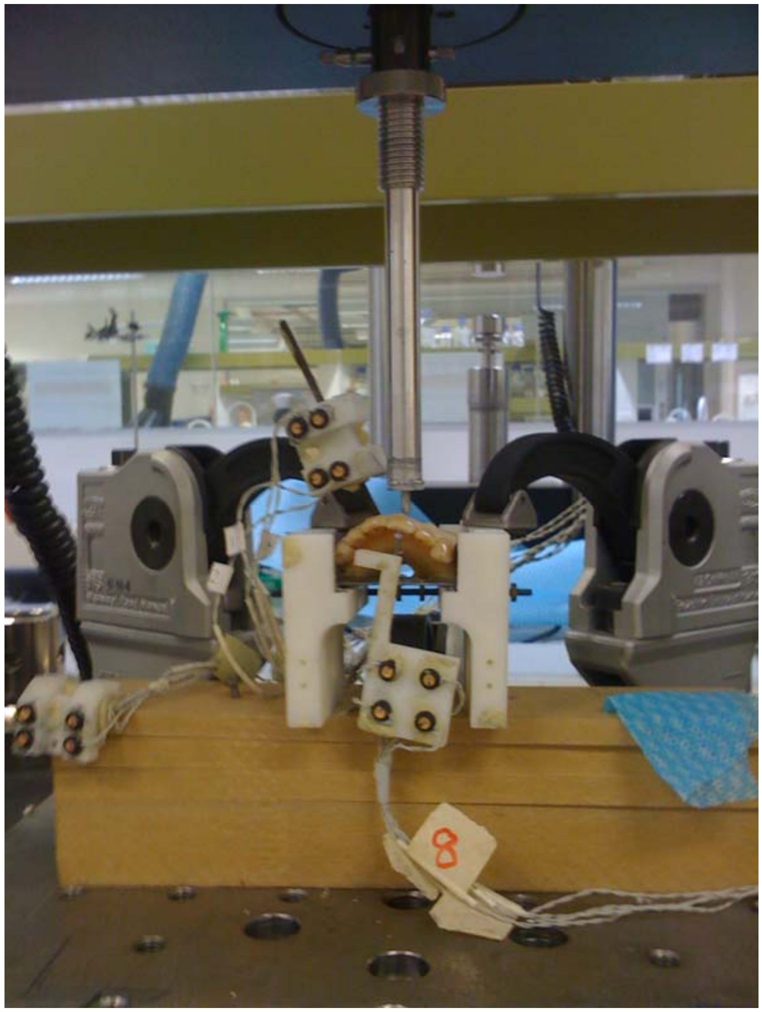

Figure 70 The long, narrow Instron attachment used in the testing of PMHS specimen 3.

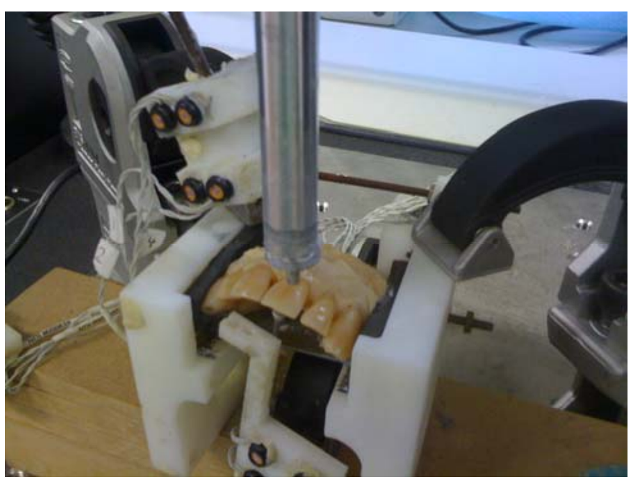

Figure 71 Top view of the alternate Instron attachment with previously used impactor tip, aligned with the front left tooth of PMHS specimen 3. Note the additional clearance room around the bone Optotrak marker holder.

Some tests on specimen 3 were also performed without the use of the RP ball and socket test rig system. The specimen was mounted to a metal plate as with specimen 2, and placed inside the RP housing and secured in place. The housing was then placed on top of a number of wooden blocks to increase its height from the Instron base plate to roughly where it was previously positioned when the ball and socket test rig was being used, and to allow for clamping of the housing to the base plate to secure the set up before applying a load (Figure 72). Obviously this set up can only be used to align the surface of a straight front tooth, and not the incisors for example, but for the purpose of the trial tests proved that the test rig could be simplified for frontal tooth loading.

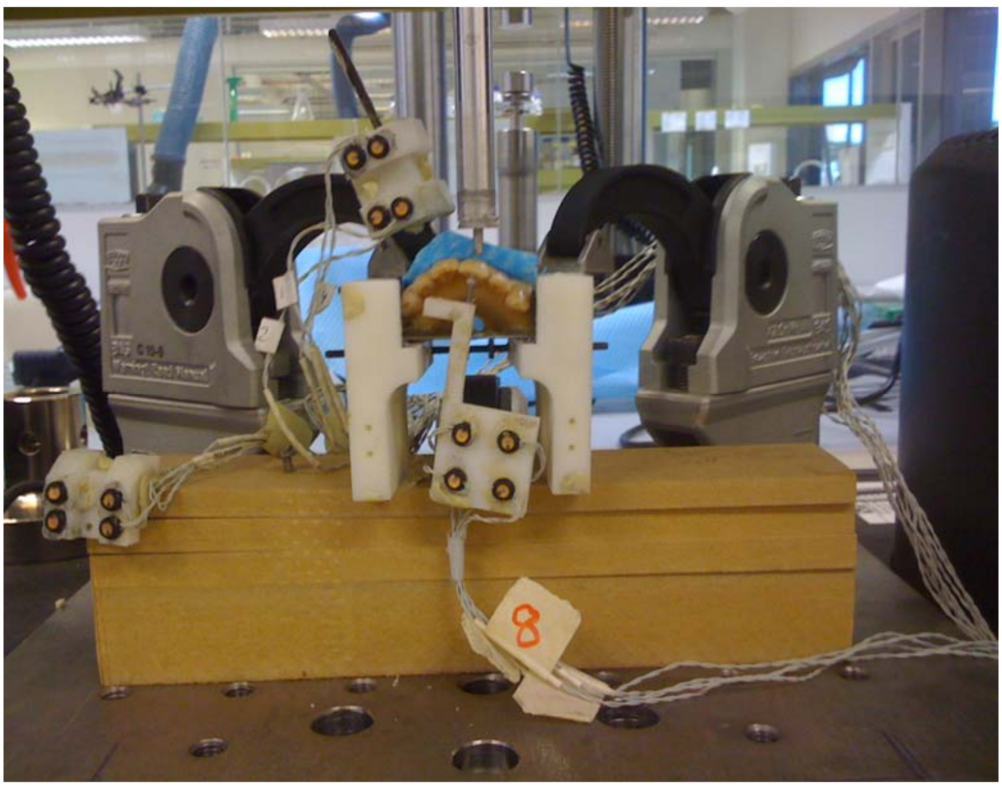

Figure 72 Simplification of test rig set up by removal of RP peg and ball and socket.

So far all the testing had been performed on the tooth surface, generally speaking in the middle of the tooth. Tests performed on specimen 3 also trialled the effects of loading the tooth up high on the gum line, with no dental cement (Figure 73). Less slippage was seen with these tests, however it is hypothesised that the injury mechanisms of luxation and the motion of the tooth and ligaments would be different, as the force was being applied closer to the anchor point of the tooth.

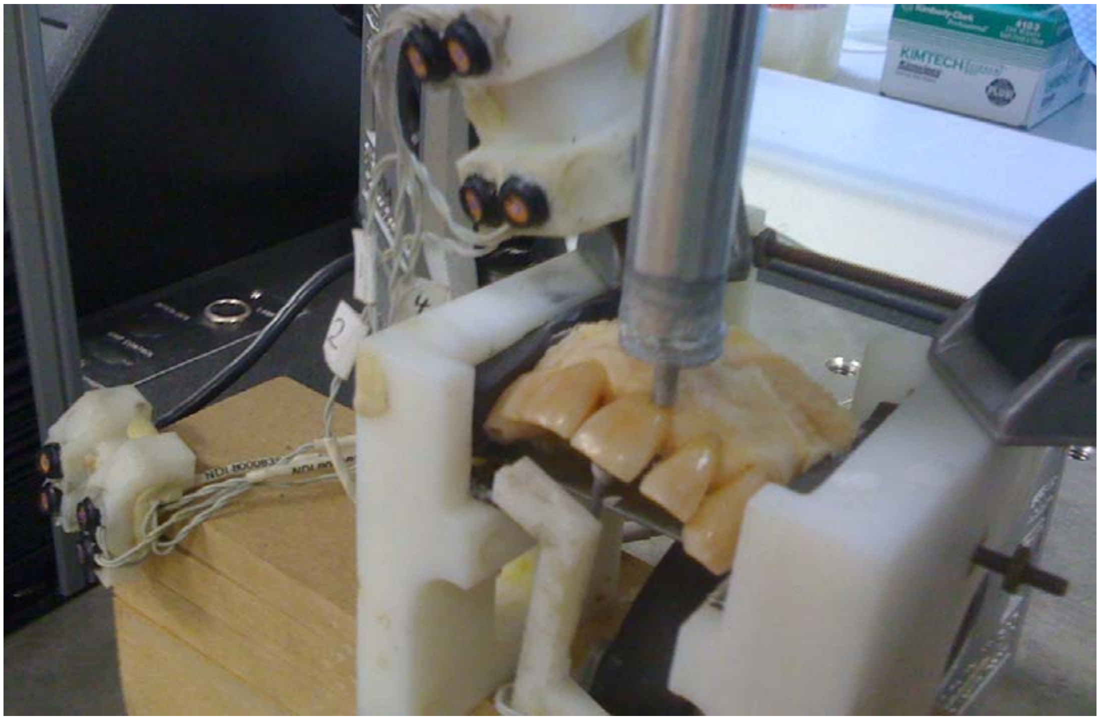

Figure 73 Impact of front left tooth of specimen 3 up high on the gum line, as opposed to the middle of the tooth surface.

The use of dental cement on the surface of the tooth with specimen 1 appeared to assist in the coupling of the impactor with the surface of the tooth, reducing the amount of slippage of the impactor on the tooth surface. The setting of the impactor in the dental cement with specimen 2 appeared to have an even greater effect. Thus, with specimen 3, the method was trialled with first setting the tack in the dental cement on the surface of the tooth before insertion into the test rig (Figure 74). Once set, the specimen was put in the test rig and the Instron attachment then only had to be aligned with the surface of the tack as opposed to the tooth. The tack presented a smooth and level surface for the Instron attachment to impact onto. It was however difficult to get the tack head perfectly aligned with the narrow Instron attachment so that the entire tack surface was loaded simultaneously. With careful manipulation perfect alignment could be achieved, however added more time and steps to the test methodology.

Figure 74 Attachment of the tack impactor to the tooth rather than the Instron machine, as trialled with specimen 3.

6.2.6 PMHS Testing Discussion and Conclusions

The PMHS testing performed in this study was limited due to a number of issues including fixation of the PMHS specimen in the test housing and too much ‘give’ in the RP test rig, however the most predominate was the unstable interaction between the impactor and the tooth surface, which was compounded by the flexing in the test rig. Previous studies have overcome this issue by acrylic embedment of the tooth specimen, Prabhakar, Jurthukoti and Kayaluizki (2005) [65], and grooving of the tooth surface, Rasmussen (1976) [77], however due to the nature of this study these options were not appropriate. This study showed that a small amount of dental cement on the surface of the tooth to hold the impactor in place could be successful without altering the tooth’s condition or mechanical capabilities.

The testing demonstrated the capability of the test design to undertake the tests required and gather the appropriate load and displacement data, however, it showed that the test rig itself required further development, most likely in the form of a metal construction as this would be much stiffer than the rapid prototyped rig used.

The Optotrak marker system, although proven to be able to measure the deformation levels occurring under these impacts, needs more consideration when attaching to the test set up to prohibit undesired interference contact, and to ensure all markers are and remain visible by the Optotrak receiver throughout the test.

The testing did not achieve the desired results of defining quantitatively the amount of deformation and level of force required to produce permanent injury to the dentition, as no visually assessable injury occurred. It is highly recommended that future testing use post-test micro CT scanning of the specimens to assess for damage not visible with the naked eye. This was originally proposed for this study however was unable to be performed when required.

The testing did, however, define some mechanical characteristics of the teeth tested in PMHS Tests 3, 4, 8 and 9 as follows:

- PMHS Test 3 (front left tooth of specimen 1) – 1.98mm of vertical movement under a load of 50N (applied at a rate of 1mm/min).
- PMHS Test 4 (front right tooth of specimen 1) – 1.6mm of vertical movement under a load of 45N (applied at a rate of 1mm/min).
- PMHS Test 8 (front right tooth of specimen 2) – 2.3mm of vertical movement under a load of 114N (applied at a rate of 3mm/min).
- PMHS Test 9 (front left tooth of specimen 2) – 2.5mm of vertical movement under a load of 158N (applied at a rate of 3mm/min).

For all the failures, however, large successes were had, with the testing proving that tooth strength and tooth compliance can be measured with an Instron and Optotrak Marker System. It showed that the results obtained by the Instron machine were able to identify when movement of the specimen occurred and when slippage of the impactor occurred. The Optotrak marker traces supported the Instron results, showing more detail of when and how the slippages occurred and to what extent, and were able to identify very small movements. The testing also showed the ability of micro CT scanning in visualising the condition of the tooth, root and PDL. This study was the first of its kind, and resulted in a method for testing the amount of deformation and level of force required to produce permanent injury to the dentition, which will pave the way for future testing and investigations of tooth biomechanics.

7. Conclusion

Mouthguards are designed and constructed to reduce the potential of injury to the teeth. How this is done, however, is left up to the manufacturer, as there is no currently available information on what levels of force or amount of deformation a tooth can withstand before injury occurs. Even if this information was available, there is no standardised way for manufacturers to test their mouthguard's ability to prevent this level of force or deformation from being transmitted to the dentition.

This study focused on defining the characteristics of a sporting injury to the mouth to form the design basis for a test method to test the amount of deformation and level of force require to produce permanent injury to the dentition. Before developing a test methodology, a test series was commissioned on an existing test apparatus manufactured by Biokinetics and Associates, to assess the methodology and equipment currently available for impacts to the maxillofacial region. The testing showed that although the mouthguards may reduce the applied force transmitted to the dentition, there is no way of telling if it is reduced by enough to substantially make a difference to the injury outcome. The testing also revealed that the assessment of upper dentition forces was being done as a whole maxilla entity as opposed to individual tooth structures, therefore supporting the need for this study in developing a test methodology that can assess intact, naturally supported tooth biomechanics.

Controlled direct loading to a specimen fixed in a ball and socket housing to enable three dimensional rotation of the specimen to present a desired tooth surface to the impactor was developed. The test utilised an Instron machine for administering and recording the load applied to the specimen, and an Optotrak marker system for tracing the movement of the tooth specimen with respect to the intact, supporting maxilla and the test rig. The test method was initially trialled on a first of its kind rapid prototyped maxilla and dentition specimen, made from a CT scan of a Post Mortem Human Subject. After successfully proving the ability of the test equipment to measure the strength and compliance of a tooth, and the test rig in housing the specimen, testing was performed on three PMHS specimens.

The PMHS testing positively revealed the hidden ability of micro CT scanning to visualise the tooth and its supporting structures, and an extension to the project would be to scan post test, in an attempt to identify any damage sustained to the tooth and or supporting structures that is not detectable by visual inspection. However a number of issues were exposed in the test methodology, most significantly with the lack of stable interaction between the impactor and the tooth surface. Although this was overcome through the use of dental cement as a bonding agent between the impactor and the tooth, many other issues including interference of the test rig with the Optotrak markers, slippage of the specimen within the test housing and 'give' in the rapid prototyped test rig contributed to the lack of a quantifiable figure for defining the strength and deformation limits of a tooth. Although the presented test rig allows for more adaptable impact orientations than the Biokinetics test rig, it is not currently capable of testing at the higher impact dynamic speeds the Biokinetics test rig accommodates. It is hoped that with further investigations and future studies based on this thesis, the necessary biomechanical data will be available to be incorporated into existing headforms, such as the Biokinetics headform, to make them more biofidelic by including the dentition.

The test method presented and trialled provides a strong basis for the development of a more refined test methodology. The importance of such a test methodology can't be stated any more clearly. Gaining knowledge on the biomechanics of the teeth will in time allow for the development of a biofidelic test surrogate, allowing mouthguards to be tested in a formed condition on the maxilla with individual teeth present, as opposed to the simple materials test currently performed. Although this testing used cadaveric specimens of questionable relevance given the issues of their age and treatment post mortem, the value of designing the test methodology that allows for placement of all types of cadaver specimens is instrumental in gaining the information required to develop a 'generic' law of the biomechanics of the dentition in a sporting population to construct a dentition model that can not only be used in this way, but also be used in studies to determine the relevance of considering the interactions between the jaw, dentition and mouthguard.

This will enable the injury protection offered by mouthguards to meet the injury tolerance level of the teeth, improving the protection offered to wearers, and reducing the seriousness and occurrence of dental injuries. With the increasing number of people around the world playing sport, this will provide significant benefit to society.

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Appendix A – Test Protocol

Test Series on "Biomechanics of teeth"
Test protocol

Aim:
To define the characteristics of human embalmed cadaveric teeth and their supporting structures under a quasi-static load in terms of force and deflection.

Equipment:
1 x excised human cadaveric maxilla with 6 anterior upper teeth and gum section intact
1 x test rig including:

- 1 x RP Base plate
- 1 x RP sleeve with rubber seal and 6 x M10 bolts, nuts & washers
- 1 x RP spherical adjustment ball and peg insertion hole with 2 x M3 threaded hex key screws and self-threaded inserts
- 1 x RP peg insertion
- 2 x RP jaw grips with 4 x 3mmx100mm threaded rod sections and 8 nuts
- 1 x strip of foam padding
- 4 x clamp downs
- 1 x metal Instron base plate with screw holes

30kN Instron test machine with:

- Bluehill software
- Small sized 'V' jaws
- Wedge grip
- 5kN load cell
- 1 x 4mm (ϕ) flat head impactor
- Dental Putty

Optotrak Northern Digital Inc (NDI) scanner and data acquisition box with NDI 6D architect & First Principals software and sensors as follows:

- 1 x rigid body for tooth (4 sensors)
- 1 x rigid body for maxilla (4 sensors)
- 1 x rigid body for Instron cross-head (4 sensors)
- 2 x rigid body for test rig – peg and base plate (8 sensors)
- Dental putty

1 x camera

Procedures

Test rig set up:

1. Attach ball and sleeve to the RP base plate using the screws.
2. Attach RP base plate to metal base plate with clamps.

Instron machine set up:

1. Attach metal base plate to the Instron machine with screws.
2. Insert impactor into V jaws.
3. Insert V jaws into wedge grip.
4. Attach wedge grip.
5. Set up software for impacts at a speed of 1mm/min (or 3mm/min) as required.
6. Apply dental putty to tip of impactor.

Specimen Preparation:

1. Visually and physically inspect the condition of the cadaver's teeth as far as possible.
2. Scan the cadaver to ascertain any signs of dental work (including bridges, fillings, implants etc.) and disease (including gingivitis – no gums, tooth decay – hollow teeth etc).
3. Excise the maxilla from the cadaveric specimen keeping the whole section intact and allowing excess bone.
4. Trim the excised specimen to within 75mm (length) x 35mm (ϕ) to fit into the micro CT large sized canister.
5. Prepare specimen for transport according to SOPs. Transport specimen for scanning and testing according to SOPS.
6. Micro CT the excised specimen for pre-test condition of the teeth, roots and supporting structures for defining the proportions of dentin to enamel, length of roots, thickness of periodontal ligament etc.
7. Wrap the specimen in glad wrap ready for testing. Store according to SOPs until ready for testing.

Optotrak set up:

1. Position the optotrak scanner at least 1.5meters away from the item being scanned.
2. Ensure all three LEDs have clear lines to the sensors, and the lens caps are removed.
3. Position the sensors on the rigid bodies, and fix the rigid bodies to the desired locations on the test specimen, the test rig and the Instron machine.
4. Plug the sensor cables into the strobers and connect the strobers to the ports of the data acquisition box.
5. Open NDI 6D software architect and construct the rigid bodies and set up the test.
6. Ensure the sensors are working and the 'save file' is where intended.

Full Test procedure:

Note: This test procedure includes frontal and uppercut type impacts. The tests performed in the study however were limited to only frontal impact loading as the test procedure required modification as testing occurred due to unforseen challenges. This test procedure holds as a basis for any further investigations or testing of tooth specimens.

1. Prepare the specimen.
2. Transport the specimen from storage at MERF to the test lab at IHBI.
3. Perform pre-test micro CT scan of the specimen.
4. Assemble the rig on the Instron machine, and load the Instron test program (as above).
5. Attach the Optotrak sensors and load the test program (as above).
6. Note the global co-ordinate system used.
7. Photograph the specimen.
8. Place the specimen in the test rig orientated for frontal impacts.
9. Photograph the test set up.
10. Perform the frontal impact testing according to the test matrix in Table 1.
11. Save results.
12. Photograph the specimen and test set up.
13. Re-orientate the test rig for uppercut impacts.
14. Photograph the test set up.
15. Perform the uppercut impact testing according to the test matrix in Table 1.
16. Save results.
17. Photograph the specimen and test set up.
18. Remove the specimen from the test rig.
19. Photograph the specimen.
20. Perform a post-test micro CT scan of the specimen to quantify the damage sustained during the testing.
21. Return the specimen to MERF.
22. Analyse Instron and Optotrak results.

Table 1 – Test matrix

<table>
<tr><th>Test Number</th><th>Tooth ID (according to Table 2)</th><th>Tooth description</th><th>Impact Direction</th><th>Force applied</th><th>Comment</th></tr>
<tr><td>1</td><td>8</td><td>Upper Right Front</td><td>Frontal</td><td>50N
Cycle up to 50N - 5 times</td><td>Perform test on middle to ensure no damage is done to surrounding teeth
Perform lowest tests first to ensure no damage.</td></tr>
<tr><td>2</td><td>10</td><td>Upper Left Incisor</td><td>Frontal</td><td>100N</td><td></td></tr>
<tr><td>3</td><td>6</td><td>Upper right canine</td><td>Frontal</td><td>200N</td><td></td></tr>
<tr><td colspan="6">**if clearly no damage visible to the teeth, and the tests appear to return linear responses on the Instron trace (i.e. there is no permanent deformation of or damage to the tooth or surrounding and supporting structures) in tests 1, 2 and 3 continue testing according to table 3.
If there are signs of permanent deformation or damage in test 3 but not test 1 or 2, clearly record this and continue testing according to table 4.
If there are signs of permanent deformation or damage in test 2 or 3, but not test 1 clearly record this, and continue testing according to Table 5.</td></tr>
<tr><td>4</td><td>9</td><td>Upper left front</td><td>Uppercut</td><td>50N
Cycle up to 50N - 5 times</td><td></td></tr>
<tr><td>5</td><td>7</td><td>Upper right incisor</td><td>Uppercut</td><td>100N</td><td></td></tr>
<tr><td>6</td><td>11</td><td>Upper left canine</td><td>uppercut</td><td>150N</td><td></td></tr>
<tr><td colspan="6">**if clearly no damage visible to the teeth, and the tests appear to return linear on the Instron trace (i.e. there is no permanent deformation of or damage to the tooth or surrounding and supporting structures) in test 4, 5 and 6 continue testing according to table 3.
If there are signs of permanent deformation or damage in test 6 but not test 4 or 5, clearly record this and continue testing according to table 4.
If there are signs of permanent deformation or damage in test 5 or 6, but not test 4 clearly record this, and continue testing according to Table 5.</td></tr>
</table>

Table 2 – universal tooth numbering system, from the ADA.

<table>
<tr><th colspan="2">Permanent Teeth</th></tr>
<tr><th>upper left</th><th>upper right</th></tr>
<tr><td>16 15 14 13 12 11 10 9</td><td>8 7 6 5 4 3 2 1</td></tr>
<tr><td>17 18 19 20 21 22 23 24</td><td>25 26 27 28 29 30 31 32</td></tr>
<tr><th>lower left</th><th>lower right</th></tr>
</table>

Table 3 – Test Matrix continued for no damage to the teeth after Tests performed in Table 1

Test Number	Tooth ID (according to table 2)	Tooth description	Impact Direction	Force applied	Comment
7	6	Upper right canine	Frontal	250N	
8	10	Upper Left Incisor	Frontal	300N	
9	8	Upper Right Front	Frontal	350N	
10	11	Upper left canine	uppercut	200N	
11	7	Upper right incisor	Uppercut	250N	
12	9	Upper left front	Uppercut	300N	

Table 4 - Test matrix continued for damage during Test 3 or 6 in Table 1

Test Number	Tooth ID (according to table 2)	Tooth description	Impact Direction	Force applied	Comment
7	10	Upper Left Incisor	Frontal	250N	
8	8	Upper Right Front	Frontal	300N	
9	9	Upper left front	Uppercut	200N	
10	7	Upper right incisor	Uppercut	250N	

Table 5 - Test matrix continued for damage during Tests 2, 3 5 and or 6 in Table 1

Test Number	Tooth ID (according to table 2)	Tooth description	Impact Direction	Test description	Comment
7	8	Upper Right Front	Frontal	250N	
8	9	Upper left front	Uppercut	200N	

Appendix B – Required mechanical properties of mouthguards in DD 253:2001

<u>FIT TEST</u>

- *4.5 When subjected to a pull test with a force of 1N (in accordance with 5.5.2) the mouthguard shall not come off the jaw cast.*
- *5.5.2 …Wet the mouthguard with water and press onto the appropriate jaw cast. Apply a force, at 90±10º in the plane of the occlusal plates, to the edge of the lingual flange between the central incisors, in an attempt to pull the mouthguard off the jaw cast. … Increase the force to 1N over a period of 30s to 60s. Maintain the force at 1±0.05N for 30s ±10s.*

<u>IMPACT/FORCE TEST</u>

- *4.6 When specimens are tested in accordance with 5.6 the maximum transmitted force shall be 3kN.*
- *5.6.1 … Test apparatus – use an anvil which has an upper domed surface with a radius or curvature of (35±0.5) mm. The striker shall have a mass of (2500±100) g. The striker face shall have a central flat region not less than 30mm in diameter.*
- *5.6.2 … Test method – use samples of new, unformed material, assembled into test specimens in the same manner as used in the manufacture of mouthguards, with at least one substantially flat area at least 30mm in diameter. After 24±2 hrs in 40±2 ºC distilled water, the specimens are impact tested 5 times with a minimum of 15 minutes between tests. Impact centres shall be more than 30mm apart. Impact energies are given in* **Error! Reference source not found.**.

Table 1 Test specimen thickness and impact energies as defined in DD253:2001

Test specimen type	Thickness, t (mm)	Impact energy (J)	
		Performance level 1	Performance level 2
Occlusal plate	1.5 to 2.0	0.25t	0.5t

Labial flange	3.0 to 4.0	where t is thickness (mm)	where t is thickness (mm)

- *In cases where doubt exists as to whether the tests on the unformed mouthguard material are representative of the material after manufacture of the mouthguard, test specimens with dimensions as close as possible to those specified above shall be cut from the mouthguard on the completion of other testing. These specimens shall be impact tested in accordance with 5.6. If the mean peak force value is more than 10% above that from the test specimens of unformed material, it shall be used to assess the performance level of the mouthguard.*

CONSTRUCTION STRENGTH

- *4.8 When tested in accordance with 5.8, mouthguards shall not pull apart at forces below 200N.*
- *5.8 … clamp the ends of the labial flanges of the mouthguard in the jaws of a constant rate of travel tensile testing machine and set it to draw the ends of the labial flanges apart at a rate of (50±25)mm/min until the mouthguard tears apart or snaps, or a force of 200N is reached. If a force of 200N is reached, maintain that force for 1 min.*
- *4.9 For mouthguards with a laminated construction, the peel strength of the bond between any two layers of the mouthguard shall be at least 4N/mm when tested in accordance with 5.9.*
- *5.9… firmly clamp one of the free ends of the test specimen into each of the jaws of the tensile testing machine. Operate the tensile testing machine with a jaw separation rate of 100±20 mm/min until either a bonded length of 20mm has been peeled or one of the adherents tears through.*